

**MONTREAL PROTOCOL
ON SUBSTANCES THAT DEplete
THE OZONE LAYER**



U N E P

**1994 Report of the
Flexible and Rigid Foams
Technical Options Committee**

1995 Assessment

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**Montreal Protocol
On Substances that Deplete the Ozone Layer**

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for the
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of the



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pursuant to
Article 6
of the Montreal Protocol;
Decision IV/13 (1993)
by the Parties to the Montreal Protocol

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**1994 UNEP FLEXIBLE AND RIGID FOAMS
TECHNICAL OPTIONS REPORT
EXECUTIVE SUMMARY**

Key Conclusions

- In 1993, the foam plastics industry reduced CFC consumption by 50% since 1986, despite a 45% increase in the size of the foam market over that period.
- Zero ODP alternatives are the substitutes of choice in many applications including packaging, cushioning and certain rigid thermal insulation foams.
- In several markets and for certain applications HCFCs are necessary for rigid thermal insulating foams and automotive integral skin foams until zero ODP solutions are proven including high energy efficiency or properties required for safety.
- CFC phaseout for developing countries is technically feasible around the year 2000 provided that Multilateral Fund projects are implemented without delay.
- The main zero ODP solutions still to be proven are liquid HFCs. In addition, broader qualification of hydrocarbons is also required. This situation is likely to be resolved around the year 2000.
- Once zero ODP solutions have been proven, and are commercially available, the implementation can be relatively rapid (3-5 years) for foam manufacturing in developed countries.
- Full recovery and recycling of CFCs from the existing stock of foam is logistically and technically difficult.

Summary of CFC Reduction in Foams Sector Since 1986

Historically, the fully halogenated chlorofluorocarbons (CFCs) used by the foam plastics manufacturing industry have been extremely varied. An assortment of CFCs, such as CFC-11, CFC-12, CFC-113 and CFC-114, and methyl chloroform, have been used in numerous foam plastic product applications. The types and major applications of foams which used CFCs are summarised in Table ES-1.

Table ES-1 Major Applications and Types of Foam Which Used CFCs

INSULATION	Construction	Polystyrene	Boardstock
		Polyolefin	Pipe
		Rigid Polyurethane	Boardstock/Flexible Faced Laminates
			Sandwich Panels
			Spray / Pour-in-Place
			Slabstock
			Pipe-in-Pipe
		Phenolic	Boardstock
			Pipe
	Appliance	Rigid Polyurethane	Refrigerators/Freezers Picnic Boxes/Other
PACKAGING	Transport	Rigid Polyurethane	Sandwich Panels
		Polystyrene	Sandwich Panels
	Sheet	Polystyrene	Single Service Uses Food Packaging Misc. Packaging
		Polyolefin	Furniture Cushion Packaging
	Non-Insulation Rigid	Polyurethane	
	Moulded	Polyolefin	Cushion Packaging
	Boardstock	Polyolefin	Cushion Packaging
	Slabstock	Flexible Polyurethane	Automotive Interiors
			Carpet Underlay
			Furniture
			Bedding
CUSHIONING	Moulded	Flexible Polyurethane	Furniture
			Automotive Cushioning
			Auto Bumper Systems
	Moulded	Polyolefin	Auto Bumper Systems
SAFETY	Integral Skin	Polyurethane	Steering Wheels/Headrests
	Sheet	Polyolefin	Flotation - Life Vests
	Board	Polyolefin	Flotation
		Polystyrene	Flotation

This report details the available technical options that can be implemented by each foam type to eliminate CFC usage as of 1994. Updates on the progress of each product in reducing CFC consumption since 1986 (summarised in Figure ES-1) are also provided.

It should be noted that specific technical options and the extent of CFC reduction achieved to date vary depending upon the foam application, market sector and applicable energy efficiency requirements. Consequently, key factors affecting the total elimination of ozone depleting substances from the foam plastics manufacturing industry are also discussed.

Overall, significant progress has been made in phasing-out CFCs in the foams sector. The foam plastics industry has reduced total CFC consumption by 50% since 1986, from 267,000 tonnes in 1986 to 133,000 tonnes in 1993. Globally, CFC consumption has either been reduced or eliminated in every market sector since 1986, despite a 45% increase in the size of the industry over the last eight years.

Reductions have been achieved by CFC conservation, product reformulation, direct substitution of CFCs with other blowing agents, not-in-kind substitutes or the use of new manufacturing technologies. In general, the greatest reductions in CFC consumption have been achieved by developed nations. For the developed countries the transition out of Annex A, Group I substances will essentially be completed in 1994, except limited use for rigid polyurethane foams for home appliance insulation. As discussed later, developing countries also are working to achieve similar CFC reductions and may not require the additional time to phaseout that the Montreal Protocol allows.

There was only one essential use nomination in the sector for 1996 relating to CFC use for analytical/laboratory uses in alternative blowing agent research. The Foams Technical Options Committee, the Technology and Economic Assessment Panel and the Open-Ended Working Group were unable to recommend this nomination to the Parties of the Protocol. The Parties decided at their October 1994 meeting not to grant an essential use for foams. Given the availability of CFC substitutes for blowing agents, few or no additional essential use nominations are anticipated in the foam plastics sector.

HCFCs are the major current alternative for rigid thermal insulation foam and certain other applications. It is estimated that 60,000 tonnes of HCFCs were used in 1993. The 1993 CFC and HCFC use estimates fail to reflect the current progress being made by the foam industry to eliminate CFCs. The real transition year for phasing out CFCs in the foam sector is 1994.

Phaseout Status in Developed Countries

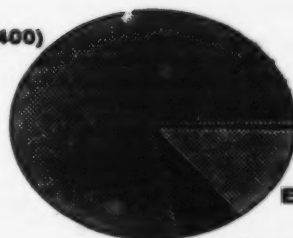
Packaging foams have completed the phaseout of CFCs. However, in developing countries there is still over 12,000 tonnes of CFCs used for extruded polystyrene packaging products despite the widescale availability of alternatives.

**Figure ES-1 CFC Consumption by Foam Sector
(tonnes)**

1986

(267,400)

Polyurethane (209,400)



Phenolic (1,400)

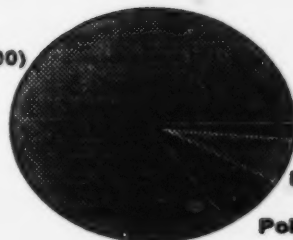
Extruded Polystyrene (37,600)

Polyolefin (19,000)

1990

(174,150)

Polyurethane (147,100)



Phenolic (2,700)

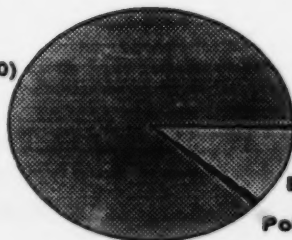
Extruded Polystyrene (12,000)

Polyolefin (12,350)

1993

(133,250)

Polyurethane (117,300)



Phenolic (650)

Extruded Polystyrene (14,400)

Polyolefin (900)

Elimination of CFCs in cushioning foams nears completion. By end of 1994 worldwide use of CFCs in this application will have been eliminated. Continued use of CFCs are likely in developing countries and Eastern Europe.

Rigid thermal insulation foam has reduced CFC use by 45% in 1993. By the end of 1994, CFC use will be essentially phased out, with limited use in the appliance foam sector until mid-1995.

Automotive Foams for Safety (Integral Skin) is near complete in phasing out CFCs. Foams used for automotive safety will have virtually eliminated CFCs by the end of 1994.

Although significant progress has been made in the replacement of CFCs in foam manufacture, no single solution has emerged from the transition process. Choices must be retained to allow optimal solutions for given applications, producer-specific and country-specific circumstances. Table ES-2 outlines currently available and long-term alternatives undergoing testing.

Zero-ODP Alternatives

Zero-ODP alternatives are currently the substitutes of choice in many foam types and applications. The major zero-ODP applications are:

- polystyrene, polyolefin and polyurethane for packaging with CO₂ (injected and water), hydrocarbons and HFC-152a;
- flexible polyurethane for cushioning with methylene chloride, CO₂ (water and injected), hydrocarbons, acetone and alternative technologies;
- polyurethane and polystyrene rigid insulation foams where energy efficiency and fire safety requirements can be met with hydrocarbons, and CO₂ (water and injected);
- polyurethane integral skin for non-automotive safety applications with CO₂ (water), HFC-134a and hydrocarbons.

Transitional Substances

In several markets and for certain applications HCFCs are necessary for rigid thermal insulating foams and automotive safety integral skin foams until other long term zero-ODP solutions are proven. Given the availability of zero-ODP substitutes for other foam applications, it is unlikely that there will be expanding use of HCFCs in developing or developed countries beyond the insulation or safety foam applications.

Table ES-2. CFC Alternatives Available to the Foam Industry

Foam Type	CFC Alternatives	
	Current	Long Term
Polyurethane:		
Rigid: Domestic Refrigerators and Freezers	Reduced CFC-11, cyclopentane, HCFC-141b	HFCs (-245, -356, -365), vacuum panels, hydrocarbons
Other Appliances	Reduced CFC-11, HCFC-141b, HCFC-22, HCFC-22/HCFC-142b blend, pentane, CO ₂ (water)	HFCs (-245, -356, -365), pentanes, CO ₂ (water), AB Technology
Boardstock/Flexible-Faced Lamination	HCFC-141b, pentanes, HCFC-22	HFCs (-245, -356, -365), pentanes
Sandwich Panels	Reduced CFC-11, HCFC-141b, HCFC-22, HCFC-22/HCFC-142b blend, pentane, HFC-134a	HFC (-245, -356, -365), pentanes, CO ₂ (water)
Spray	Reduced CFC-11, CO ₂ (water), HCFC-141b	HFCs (-245, -356, -365), CO ₂ (water)
Slabstock	Reduced CFC-11, pentanes, HCFC-141b	HFCs (-245, -356, -365), CO ₂ (water or injected)
Pipe	CO ₂ (water), HCFC-22, HCFC-22/HCFC-142b blends, HCFC-141b, pentanes	HFCs (-245, -356, -365), 100% CO ₂ (water)
Flexible: Slab	Extended-range polyols, CO ₂ (water and injected), softening agents, methylene chloride, methyl chloroform, acetone, AB Technology, increased density, HCFC-141b, pentane, MDI Technology, alternative technologies (E-Max, accelerated cooling, variable pressure)	CO ₂ (injected), alternative technologies
Moulded	Increased density, methyl chloroform, extended range polyols, CO ₂ (water), HCFC-141b	Extended range polyols, CO ₂ (water)
Integral Skin	HCFC-22, hydrocarbons, CO ₂ (water), HFC-134a, pentanes, HCFC-141b	CO ₂ (water), HFCs (-245, -356, -365)
Phenolic	HCFC-141b, hydrocarbons, LBL2, HCFC-22/HCFC-142b blends	HFCs (-245, -356, -365), hydrocarbons
Extruded Polystyrene:		
Sheets	HCFC-22, hydrocarbons, CO ₂ (injected), HFC-152a	CO ₂ (injected), hydrocarbons, atmospheric gases, HFCs (-134a, -152a)
Boardstock	HCFC-22, HCFC-142b, CO ₂ (injected)	HFCs (-134a, -152a), CO ₂ (injected)
Polyolefin	Hydrocarbons, HCFC-22, HCFC-142b, CO ₂ (injected), HFC-152a	Hydrocarbons, CO ₂ (injected)

The selection of an HCFC depends on the foam type and application. The major HCFC applications are:

Rigid polyurethane for appliance and construction with preferred use of HCFC-141b and minor use of HCFC-22/-142b blends;

Integral skin polyurethane for interior automotive safety components with use of HCFC-22;

Extruded polystyrene board for construction with preferred use of HCFC-142b and some use of HCFC-22;

Phenolic foam for building and pipe insulation with use of HCFC-141b; and

Polyolefin foam for pipe insulation with use of HCFC-142b.

In 1993, it was estimated that 60,000 tonnes of HCFCs were used to help achieve the CFC reductions of 50 % since 1986.

Developing Countries

Technology needs of developing countries are similar to those in developed countries except that climatic conditions can be severe and enterprises may be small.

Ozone depleting substances used in the foams sector are often devoted toward fulfilling basic societal needs such as food preservation.

The strong growth of industry in many countries makes a CFC phaseout in as short a time as is practicable, for example about 2000, a high priority so as to not increase significantly atmospheric chlorine loading. Achieving a phaseout target year of about 2000 depends on:

- quick development of country programmes,
- rapid generation of individual enterprise projects which are as cost effective as possible so as to make best use of the MLF,
- avoiding the use of intermediate technologies which can result in costly replacement,
- making most efficient use of national institutes,
- using local alternatives where possible and provided that they are of acceptable quality,
- ensuring the support of governments,
- availability of sufficient experts to speed training and technology transfer, and
- availability of equipment to handle flammable and low boiling blowing agents.

ODS replacement programmes, however, should not compromise health or safety.

Long Term Zero-ODP Alternatives

The main zero-ODP solutions still to be proven are liquid HFC isomers. There also needs to be a broader qualification of hydrocarbons. This situation is likely to be resolved around 2000. In addition to technical feasibility, qualification of these blowing agents at a minimum includes:

Safety -- Uncertainties associated with the toxicity of new substitute blowing agents and exposure to possible decomposition products formed in foams must be narrowed to ensure worker and consumer safety. Safe handling procedures required for substitutes of varying degrees of flammability must also be evaluated.

Environment -- Risks to the environment must be controllable to meet local, regional and national standards. Environmental issues include restrictions on the emissions of volatile organic compounds, such as hydrocarbons, and global warming concerns.

Product Performance -- Thermal insulation and safety products must meet market and regulatory requirements including building and fire codes, consumer/market needs, and energy efficiency requirements. This is particularly important if hydrocarbons are to qualify for all products in all regions.

Cost and Availability of Alternatives -- Substitutes must be sufficiently available and affordable to allow for an orderly transition and to allow for products to be manufactured and sold competitively.

National & Regional Legislation (new or proposed) -- Transition efforts will be affected by differing national and regional legislation regulating the use of various substitutes. Legislative diversity and inconsistency can create obstacles that impede the implementation of substitutes particularly for companies serving multinational markets.

Once these zero-ODP alternatives have been proven, and are commercially available, then full implementation can be relatively rapid (3-5 years) for the foams sector.

Recovery/Recycling/Destruction

Full recovery and recycling of CFCs from the existing stock of foam is logistically and technically difficult. Where the foam can be separated from other materials, destruction of CFC and HCFC by the incineration of the foam (a destruction technology approved by UNEP) is currently the most effective option.

Chapter One

THE USE OF CFCs IN THE PRODUCTION OF FOAM PLASTICS

This report describes the use of chlorofluorocarbons (CFCs) in the production of foam plastics and foam plastic products. Prepared by the United Nations Environmental Programme (UNEP) Foam Technical Options Committee (Committee members are listed in Appendix A), this report also discusses alternatives to reduce CFC use, and includes a compilation of the Committee's findings to date.

Foam plastics that are made with CFCs and discussed in this report include:

- polyurethane;
- phenolic;
- extruded polystyrene; and
- polyolefin (polyethylene and polypropylene).

Foam plastics made with blowing agents other than CFCs are mentioned only where they may be product substitutes or where they may clarify the scope of a particular section. Expanded polystyrene and polyvinyl chloride foams are examples of plastic foams which are not made with CFCs.

In this report, a chapter is devoted to each of the four foam types made with CFCs. Each chapter discusses the various types and applications of the foam, the production process, the use of CFCs during production, and alternatives for reducing CFC use in foam manufacturing.

Introduction

Foam plastics can be classified on the basis of composition, chemical and physical characteristics, the manufacturing processes, or product applications, as shown in Table I-1. The major applications for foam plastics include thermal insulation, packaging, and cushioning.

Table I-1 Major Applications and Types of Foam Which Used CFCs

INSULATION	Construction	Polystyrene	Boardstock
		Polyolefin	Pipe
		Rigid Polyurethane	Boardstock/Flexible Faced Laminates
			Sandwich Panels
			Spray / Pour-in-Place
			Slabstock
			Pipe-in-Pipe
		Phenolic	Boardstock
			Pipe
	Appliance	Rigid Polyurethane	Refrigerators/Freezers Picnic Boxes/Other
PACKAGING	Transport	Rigid Polyurethane	Sandwich Panels
		Polystyrene	Sandwich Panels
	Sheet	Polystyrene	Single Service Uses Food Packaging Misc. Packaging
		Polyolefin	Furniture Cushion Packaging
	Non-Insulation Rigid	Polyurethane	
	Moulded	Polyolefin	Cushion Packaging
	Boardstock	Polyolefin	Cushion Packaging
	Slabstock	Flexible Polyurethane	Automotive Interiors Carpet Underlay Furniture Bedding
CUSHIONING	Moulded	Flexible Polyurethane	Furniture Automotive Cushioning Auto Bumper Systems
	Moulded	Polyolefin	Auto Bumper Systems
	Integral Skin	Polyurethane	Steering Wheels/Headrests
SAFETY	Sheet	Polyolefin	Flotation - Life Vests
	Board	Polyolefin	Flotation
		Polystyrene	Flotation

Foam plastics are produced by using gas or volatile liquid "blowing agents" to create bubbles or "cells" in the plastic structure. Thermoset foam plastics (polyurethane and phenolic) are made by introducing a volatile liquid blowing agent into liquid precursors. During the exothermic reaction between precursor chemicals to form a plastic, the liquid blowing agent volatilises to a gas, forming bubbles which create a cellular structure when the plastic hardens. In contrast, thermoplastic foams (polystyrene and polyolefin) are produced by injecting a gas blowing agent into a molten plastic resin.

In some foam plastics, the resulting cells are closed, trapping the blowing agent inside, while in others, the cells are produced open and the blowing agent escapes.

A number of materials can be used as blowing agents, among them carbon dioxide, hydrocarbons, chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs). To be considered a good blowing agent, it is required that they:

- do not react with the plastic;
- be sufficiently soluble in the liquid plastic, but insoluble in the solid plastic; and
- possess suitable boiling points and vapour pressures.

For some foam plastic products (particularly the closed-cell foams), additional blowing agent properties are required to produce specific end-product characteristics or to facilitate the manufacturing process. Product examples include:

- closed-cell insulating foams that require a blowing agent with low thermal conductivity to provide its high thermal insulation efficiency;
- some thermosetting foams (especially the low-density, open-celled flexible polyurethane foams) that rely on blowing agents to absorb some of the heat released during production;
- extruded thermoplastic foams that rely on the blowing agent to absorb some of the heat of the molten polymer; and
- resilient closed-cell foams (especially polyolefins) that require the blowing agent to provide dimensional stability during the air-aging period.

In addition, a non-flammable blowing agent is usually desired because it helps improve the safety of the foam manufacturing environment and enhances the fire performance characteristics of the end product.

Since they met these requirements and were, until recently, relatively inexpensive, CFCs had been widely used as blowing agents for foam plastics. Historically, the foam plastics industry used the following CFCs:

- CFC-11 and CFC-113 for thermosetting foams since these blowing agents are liquid chemicals; and

- CFC-12 and CFC-114 for thermoplastic foams since these blowing agents are lower boiling point gases.

This report discusses a second group of blowing agents: partially-halogenated chlorofluorocarbons (HCFCs). Featuring at least one hydrogen atom in the molecule and a carbon-hydrogen bond, HCFCs are less chemically stable than CFCs and tend to break down in the lower atmosphere. Consequently, HCFCs' ability to migrate to the stratosphere and to decompose into ozone-damaging chlorine is much lower than CFCs. Chemicals in this group include:

- HCFC-22;
- HCFC-142b;
- HCFC-141b; and
- HCFC-123.

Currently, HCFC-22, HCFC-142b and HCFC-141b are commercially available. HCFC-123 has completed toxicity testing, but it is not commercially available to the foam insulation market. HCFCs are becoming the predominant alternative to replace CFCs in most polyurethane, extruded polystyrene boardstock and phenolic rigid thermal insulating applications.

Because HCFCs contain chlorine and contribute to ozone depletion, they are considered transitional substances. In 1992, Parties to the Montreal Protocol signed the Copenhagen Amendment which agrees to phaseout allowable HCFC consumption between 1996 and 2030.

The international HCFC phaseout does not include chemical specific reductions, but some individual countries have developed domestic regulations which phase out individual chemicals. For instance in Europe in the United States, HCFC-141b is scheduled for phaseout in 2003, and HCFC-22 and HCFC-142b is scheduled for phaseout in 2010. In some European countries, HCFCs are being proposed for phaseout.

In many applications, such as packaging and cushioning foams, most if not all use of HCFCs are being eliminated. However, major research efforts are underway to find long term substitutes to eliminate the need for HCFCs in necessary applications such as rigid thermal insulation and foams for automotive safety. Much of this effort involves replacement of HCFCs with other blowing agents, such as hydrocarbons or HFCs.

Blowing agents used in foam products are released to the atmosphere at different rates, depending upon the foam type and the molecular weight of the blowing agent. For most open-cell foams, a large portion of the blowing agent is released during the manufacturing process.

In contrast, closed-cell foams retain most of their blowing agent during the manufacturing process. In insulation foam products, most often, the blowing agent is released either during

fabrication, which may break some closed cells, or gradually over the useful life and disposal of the product. Depending upon the type of blowing agent used, it will dissipate from the foam at differing rates. This is a main issue regarding the long term aging of insulation foams, which need to retain the blowing agent within the cell walls of the foam to achieve the desired and continued insulating value.

Replacing CFCs with HCFCs will provide some foam plastic sectors an important transitional period, while manufacturers, raw material suppliers, governments and other researchers work towards developing long-term solutions. Long-term candidates for some current uses are HFCs (partially halogenated fluorocarbons), hydrocarbons or alternative processes and blowing agents.

Global Consumption of CFCs in Foam Plastic Products

The foam plastics industry used approximately 133,000 tonnes of CFCs worldwide in 1993 to manufacture all types of foam plastic products. This represents a 50 percent reduction compared to the 267,000 tonnes consumed worldwide in 1986. The majority of CFC use in developed countries will be out by the end of 1994, with the exception of a few remaining uses of CFCs in appliance foam.

Technical Options to Reduce CFCs in Foam Plastic Products

There are three potential methods for reducing the use of CFCs in the production of foam plastic products:

- substituting alternative blowing agents for the fully-halogenated CFCs;
- modifying present production processes or using alternative technologies; and
- substituting foam plastic products with alternative products, sometimes referred to as Not-In-Kind (NIK) substitutes.

These technical options are briefly described here and are discussed in more detail in the body of the report.

Alternative Blowing Agents

The use of alternative blowing agents, such as HCFCs, hydrocarbons, HFCs and inert gases, have been identified as a way to eliminate CFCs. Alternative blowing agents are chemicals with many characteristics similar to CFCs, but often have significantly lower atmospheric lifetimes and, consequently, a much lower potential for depleting ozone (HCFCs), or no potential at all, such as hydrocarbons or HFCs.

Process Modifications and Technological Alternatives

Process modifications and technological alternatives include methods for reducing CFC emissions either by preventing the release of CFCs into the atmosphere during foam production or by reducing or eliminating the need for CFCs.

One method of capturing CFCs and HCFCs during the production process is carbon adsorption. Recovery technologies, however, are more effective for open-cell foams, such as flexible polyurethane foam, because of the relatively high percentage of CFCs released during the manufacturing process. In contrast, carbon adsorption is less effective for closed-cell foams, such as rigid polyurethane and extruded polystyrene, because of the relatively small percentage of CFCs released during production.

Process modifications can also take the form of new chemical systems that expand the present range of foam plastics requiring smaller amounts of CFCs. For example, the use of increased levels of water in the chemical reaction modifies the existing foam production process for polyurethane foams. Changes in polyols and other chemicals used in the foaming

part of the production process could also reduce or, in favourable cases, eliminate the need for CFCs in both rigid and flexible polyurethane foam.

New equipment is also being designed and adapted which can reduce the quantity or necessity of blowing agent. For instance, in flexible foam, variable pressure foam equipment acts to simulate "altitude" effects by allowing lower density foams to be manufactured without an auxiliary blowing agent.

Product Substitution or Not-In-Kind

Product substitutes currently compete in all subsectors of the foam market, with the possible exception of appliance insulation. The appliance manufacturing production system is based on direct automated injection of polyurethane foam raw materials between the inner and outer shell of the appliance cabinet, which facilitates the manufacturing process. The foam-in-place technology utilised is a major factor in the structural integrity of the appliance cabinet.

In some uses of flexible slabstock foam, notably the outer layers of furniture cushions and mattress ticking backing (quilting foam), fibrefill materials such as polyester batting are competitive with flexible foam. These materials have the potential to replace at least some portion of slabstock foam, principally the supersoft foams in some markets. Fire performance requirements may be limitations in some applications.

Whilst products such as paper, cardboard and expanded polystyrene can be used in many packaging applications, there are a number of special applications (such as electronic equipment packaging) where protective foam products are the most cost effective choice.

Polyurethane, extruded polystyrene and polyolefin packaging materials offer better moisture barrier protection, increased durability and better cushioning protection than more conventional materials.

Foam insulation use in buildings has significantly increased because of its high energy efficiency combined with other physical properties, including excellent combustibility test performance, waterproof characteristics, low density, thin profile and ease of handling. Some polyurethane foam insulation products can be sprayed or poured in-situ. Non-foam plastic insulation products can achieve some of these properties, but not all. In all instances, the substitution of other products would require increases in the thickness of the product to provide equivalent energy efficiency. These insulation products may become more competitive if the choice of alternative blowing agents reduces the thermal conductivity of the foam insulation.

Building design constraints, local building code requirements, and construction costs dictate the choice of insulation material. Because of these factors, it is difficult to generalise the potential substitution of non-foam insulation for foam insulations currently containing CFCs. In some instances, there are substitute products available which can provide acceptable performance. For some applications, however, there is no obvious alternative which would not involve considerable changes in design and construction practice or loss of energy efficiency (Curwell, 1988).

Evaluation of CFC Alternatives

The technical options for reducing or eliminating CFC use in foam are dependent upon each foam type, since each has a distinct set of process and product application needs. Within foam types, options can vary regionally depending upon various factors, including regional product mix, climate, political factors, environmental regulations, product specifications and energy efficiency requirements. Discussion of technical options, CFC reductions and the status of evaluating alternatives will be divided into the following categories:

- Current -- an alternative which currently has application in a specific end use; however, in some instances, all classification criterion may not be satisfied for all world regions and product types; or
- Long Term -- an alternative which requires longer term research to determine whether it can be implemented or is no longer considered an option. These options are usually considered for implementation after 1997.

HCFCs are examples of current alternatives being used in the foam industry. They are mostly being applied as alternatives in insulation products. Although considered transitional alternatives due to ozone depletion concerns, they are generally available in commercial quantities. Toxicity evaluations have been completed and they have been proven to be technically viable. Conversions to replace CFCs began as early as 1989 in the extruded

polystyrene boardstock industry and in other foam insulation sectors, conversions are either fully underway or complete.

Hydrocarbons are alternatives that are currently being used in a number of foam applications, including cyclopentane as foam blowing agent in appliance foam, and various forms of pentane in extruded polystyrene, phenolic and other polyurethane applications. But whilst hydrocarbons are commercially available and used in some regions and applications, they are still undergoing development testing and would not be able to be introduced immediately in all markets and for all products.

HFCs are also used to replace CFCs and HCFCs in some limited applications, such as HFC-152a in extruded polystyrene and polyolefin packaging foams. While HFCs may be considered a current alternative in these applications, it would not be able to be applied to other foam products. In general HFCs are seen as potential long term options in insulation applications.

Table I-2 summarises the various CFC alternatives available to the foam plastics industry. Reductions in CFC use will be achieved by using a combination of chemical substitutes, process modifications or technological alternatives, and product substitutes.

Issues Affecting the Phaseout of CFCs

The scheduled reductions of CFCs, which is described in this report for the foam plastic industry, assumes worldwide availability of substitutes and no future regulations that could restrict the ability of substitutes from being adopted on either a global or regional basis. Some of the key factors affecting further reductions in CFC and HCFC use include: safety issues, environmental concerns, product performance, availability of alternatives and national and regional legislation. These issues will be discussed further in the appropriate chapters of the report.

Table I-2. CFC Alternatives Available to the Foam Industry

Foam Type	CFC Alternatives	
	Current	Long Term
Polyurethane:		
Rigid: Domestic Refrigerators and Freezers	Reduced CFC-11, cyclopentane, HCFC-141b	HFCs (-245, -356, -365), vacuum panels, hydrocarbons
Other Appliances	Reduced CFC-11, HCFC-141b, HCFC-22, HCFC-22/HCFC-142b blend, pentane, CO ₂ (water)	HFCs (-245, -356, -365), pentanes, CO ₂ (water), AB Technology
Boardstock/Flexible-Faced Lamination	HCFC-141b, pentanes, HCFC-22	HFCs (-245, -356, -365), pentanes
Sandwich Panels	Reduced CFC-11, HCFC-141b, HCFC-22, HCFC-22/HCFC-142b blend, pentane, HFC-134a	HFC (-245, -356, -365), pentanes, CO ₂ (water)
Spray	Reduced CFC-11, CO ₂ (water), HCFC-141b	HFCs (-245, -356, -365), CO ₂ (water)
Slabstock	Reduced CFC-11, pentanes, HCFC-141b	HFCs (-245, -356, -365), CO ₂ (water or injected)
Pipe	CO ₂ (water), HCFC-22, HCFC-22/HCFC-142b blends, HCFC-141b, pentanes	HFCs (-245, -356, -365), 100% CO ₂ (water)
Flexible: Slab	Extended-range polyols, CO ₂ (water and injected), softening agents, methylene chloride, methyl chloroform, acetone, AB Technology, increased density, HCFC-141b, pentane, MDI Technology, alternative technologies (E-Max, accelerated cooling, variable pressure)	CO ₂ (injected), alternative technologies
Moulded	Increased density, methyl chloroform, extended range polyols, CO ₂ (water), HCFC-141b	Extended range polyols, CO ₂ (water)
Integral Skin	HCFC-22, hydrocarbons, CO ₂ (water), HFC-134a, pentanes, HCFC-141b	CO ₂ (water), HFCs (-245, -356, -365)
Phenolic	HCFC-141b, hydrocarbons, LBL2 (2-chloropropane), HCFC-22/HCFC-142b blends	HFCs (-245, -356, -365), hydrocarbons
Extruded Polystyrene:		
Sheets	HCFC-22, hydrocarbons, CO ₂ (injected), HFC-152a	CO ₂ (injected), hydrocarbons, atmospheric gases, HFCs (-134a, -152a)
Boardstock	HCFC-22, HCFC-142b, CO ₂ (injected)	HFCs (-134a, -152a), CO ₂ (injected)
Polyolefin	Hydrocarbons, HCFC-22, HCFC-142b, CO ₂ (injected), HFC-152a	Hydrocarbons, CO ₂ (injected)

Chapter Two

DEVELOPING COUNTRY PERSPECTIVE

Introduction and Summary

This chapter covers issues relating to the phaseout of CFCs used in the production of foamed plastics in developing countries as defined under Article 5-1 of the Montreal Protocol.

Under the existing provisions of the Protocol, the developing countries are allowed to use CFCs up to 2010 and there are no controls on HCFCs. Nevertheless, the foam manufacturers in developing countries have expressed a strong desire to transition to more ozone benign, contemporary technology for both domestic markets and to serve export markets where the norm is CFC-free products. There are also a number of foams projects submitted to the Multilateral Fund (MLF) which use non-ozone-depleting substances.

A timely conversion to CFC-free technology is especially important because the economies of many developing countries are exhibiting extremely rapid growth, particularly in the foam plastic-related sectors. If CFC use were to expand at similar rates for an extended period then the positive phase out efforts achieved by developed countries could be negated.

An evaluation of technology and circumstances in developing countries indicate that CFC phaseout in foam plastics is technically feasible around 2000. Achievement of this objective will depend on :

- Rapid development of country programmes,
- Rapid generation of individual enterprise projects which are as cost effective as possible so as to make best use of the MLF,
- Avoiding the use of intermediate technologies which can result in costly replacement,
- Effective use of national institutes,
- Using local alternatives where possible and provided that they are of acceptable quality,

- Ensuring the support of governments,
- Availability of sufficient experts to speed training and technology transfer, and
- Availability of equipment including that to handle flammable and low boiling blowing agents.

This accelerated programme, however, should not compromise health or safety.

This chapter discusses the issues concerning the phaseout of CFCs in all the foam plastics sectors in developing countries.

Foamed Plastic Markets in Developing Countries

Developing countries manufacture foam plastics in all the sectors which historically used CFCs. In most countries foam production and CFC usage per capita is low. However, in some cases CFC use growing rapidly, at up to 20% per annum.

Polyolefin and polystyrene foams are widely used for packaging applications (including food packaging). Transition away from CFCs, mostly to zero ODP alternatives such as hydrocarbons, is underway in projects financed by the MLF. However, over 12,000 tonnes of CFC-12 are still used in extruded polystyrene food packaging products, despite the availability of zero ODP alternatives.

Production levels of extruded polystyrene boards and phenolic insulating foams is comparatively low. Phenolic foam production with CFCs is currently confined to India. The demand for these products will grow as industrialisation intensifies and energy saving measures are introduced in buildings.

Rigid polyurethane foams are widely produced in developing countries. The main application is insulation for domestic refrigerators and freezers with production of these articles expanding to meet domestic market demand. This is an application where foam assists in meeting a basic societal need -- that of food preservation and supply. Other major applications include commercial appliances, insulated panels and spray foam. There is currently little or no production of boardstock/flexible faced lamination in developing countries.

The CFC phaseout options for rigid polyurethane insulation varies, however, many are switching to zero ODP technologies. A number of enterprises are following the European technology trend to pentane in appliance foams. Whilst this gives a long term solution it places a heavy emphasis on appropriate equipment replacement and safety training and procedures. Energy efficiency is also an important consideration in developing countries, and substitution to zero-ODP chemicals can reduce efficiency if there is no compensation for generally higher thermal conduction.

The polyurethane flexible foam sector is large and, in many cases, well advanced in its plans to phase out the use of CFCs. The main option chosen to replace CFC-11 in slabstock is methylene chloride, which means the provision of adequate health and safety precautions. Some of the many developments in alternative equipment will also be used. Moulded flexible foams are mainly converting to all CO₂ (water) blowing and integral skin foams to a variety of solutions which include HCFCs.

The Provision of Technology - Imported and Indigenous

The majority of developing countries will be relying on imported technology. This will be provided mainly by multinational chemical suppliers who have the capability to deliver technology on a global basis. The competition between the chemical suppliers will help to ensure that developing country enterprises are offered contemporary technology.

A second source of technology transfer is transplants of developed country enterprises. This is particularly true of the Asia Pacific region where there are many enterprises partly owned by Japanese companies.

Another important technology conduit is the foam machinery companies, many of whom operate on a global basis. They have a key role in equipping the developing country enterprises with state-of-the-art equipment and in training the operatives in its safe use. The ability of these machinery companies to meet demands over the next five years will be a critical factor in successfully meeting an accelerated phaseout of CFCs in the foams sector.

Some large developing countries, particularly China and India, have an infrastructure which allows the development of indigenous technologies. They have the necessary technological institutes to research technology which can support local raw material manufacturers. For example, institutes have developed the technology and manufacture polyol formulations for rigid polyurethane foam. Large institutes can also verify replacement technologies.

In addition, Brazil, China and India have local production of CFCs and emerging production capability for HCFCs. CFC phaseout in some of the foam sectors may have to consider options which may differ from the dominant choices in developed countries to take account of national manufacturing strategies and the economics accruing from using local, rather than imported blowing agents.

Enterprises should also be aware of the need for blowing agent alternatives of the correct, foam blowing, quality.

Technology Choices

The technological requirements of developing countries are no different to those in developed countries. For example, to reduce climate change and conserve electricity, the foams used in

domestic refrigerators should have the best practicable thermal insulation in line with technology being applied in developed countries.

Developing country enterprises should also choose from a range of technologies to help ensure that the market needs (including climatic) are met.

Another key consideration is to look for technologies which, if possible, achieve the transition to zero ODP technology in one step. This can save the time and capital expense of a multistage strategy and reduce the demand on the MLF. However, this may not be possible in all cases. Care should be taken in avoiding equipment redundancies involved with the intermediate step or steps. Cases where a one step strategy may not be applicable depends on exports to developed countries where a transitional technology is the norm.

Health, Safety and Environmental Considerations

All CFC phaseout projects should ensure that the best health and safety practises are transferred to the developing country enterprises. The projects should always have an adequate provision for training of operators and mandate that post implementation audits are carried out on a regular basis. Examples of substitutes with associated risks are flammable blowing agents and non-ozone depleting chlorinated chemicals such as methylene chloride. Care should be taken to ensure health and safety standards are met.

Provision should also be made to ensure that regulatory limits restricting the emissions of volatile organic compounds which contribute to the formation of ground-level ozone (smog) are met. The global warming potential of alternatives should also be taken into account when choices are being made.

Information Sources and Other Considerations

Developing country enterprises are being informed of the need to phase out CFCs and of the options to achieve this by a number of institutions. An important mechanism is via UNEP with its range of workshops and its 1994 publication of a catalogue of foam technologies.

A final important factor is national government commitment to the CFC phaseout and to the affected enterprises. This commitment should include the rapid development of country programmes and the availability of expertise from both developed and developing country sources in the next few critical years.

Chapter Three

POLYURETHANE FOAMS

Polyurethane foams are generally based on the exothermic reaction of isocyanates and polyols. By itself, the polymerisation reaction produces a solid polyurethane. During a process known as foam blowing, polyurethane foams are made by forming gas bubbles in the polymerising mixture. The "blowing agent" can be either a gas chemically formed by water or formic acid reacting with the isocyanate, or a physical blowing agent such as low boiling inert organic compounds separately introduced into the reaction.

Used in a large variety of products, polyurethane foams can be classified into three major categories: rigid, flexible and integral skin. Product applications include insulating materials for buildings and appliances, cushioning products for furnishings and automobiles, packaging for protection of high-value products, and automobile bumpers and instrument panels.

CFCs, particularly CFC-11, have been used to produce all of these foam products. In 1990, 147,100 tonnes of CFCs were used in the manufacture of polyurethane foams, reduced from 209,400 tonnes in 1986. For 1993, CFC use for polyurethane foam production was estimated at approximately 117,300 tonnes, a 44% reduction compared to the 1986 consumption figure. Polyurethane foams accounted for approximately 88% of the total amount of CFCs used in all foam plastic production in 1993.

Each type of polyurethane foam, its use of CFCs, and the technical options available to reduce CFC consumption are discussed below.

RIGID DOMESTIC REFRIGERATOR AND FREEZER INSULATION

Products and Applications

Rigid polyurethane foams continue to be the dominant insulation used in refrigerators and freezers. In these products the foam serves as a key element in the structure of the appliance, as well as a very effective insulation. The foam must have adequate compressive and flexural strength to ensure the integrity of the product under extreme temperature conditions during shipping, as well as heavy loading during usage of the appliance. It must maintain both its insulation effectiveness and structural properties throughout the design life of the product. Using CFCs, foam manufacturers were successful in developing formulations which met all of these requirements. As substitutes are developed, care must be taken to ensure that properties are not compromised to the extent that the overall performance of the appliance is degraded.

Although the basic requirements for refrigerator/freezer foam insulation are similar for most manufacturers, unique manufacturing facilities, local market conditions and regulatory

requirements result in a situation where unique requirements exist for specific markets. For example, the importance of energy consumption in the US and Japanese markets has influenced manufacturers to use formulations with higher levels of CFCs to achieve lower conductivities than are required in the European market.

Production Process

Liquid chemicals are injected between the outer shell and the interior liner of an appliance cabinet where they react, flow and expand to form rigid polyurethane foam throughout the cavity. Substantial fixtures are provided to support the walls which are under pressure from the foam. Typically, a few percent of the blowing agent escapes from the chemical mixture and is vented during the foaming process. Production systems do not readily lend themselves to recovery of this lost blowing agent, so it has generally been vented directly to the atmosphere.

Over time, foam suppliers have developed formulations (using CFCs) which have properties (viscosity, reaction speed, exotherm, etc.) that meet the needs of production processes. With any new blowing agent, these properties must be maintained in order to produce quality products and control costs.

Global Consumption of CFCs in Rigid Insulation for Refrigerators and Freezers

The global usage of CFCs in refrigerator and freezer foam in 1993 is estimated to have been 32,100 tonnes. By 1993, many appliance manufacturers had already implemented major reductions in CFC-11 content where conditions allowed. However, in some markets such as the US, other factors, including energy regulations, safety concerns, and the need to develop plastic liners resistant to attack from the new blowing agents have limited the industry's ability to rapidly reduce consumption.

The phase-out of CFCs accelerated in some markets during 1994. It is estimated that by the first of January, 1995 the phase-out of CFC-11 will be essentially complete in the European and US markets.

Table III-1. Estimated Global CFC Consumption for Refrigerator and Freezer Insulation in 1993

Region	Tonnes 1993
North America	8,600
Western Europe	4,400
Eastern Europe	2,800
Middle East/Africa	2,200
Central/South America	1,900
Japan	2,300
Asia Pacific	9,900
Total World	32,100

Global Consumption of HCFCs in Rigid Insulation for Refrigerators and Freezers

In 1993 the consumption of HCFCs in appliances was relatively low. A variety of chemicals, including HCFC-141b, HCFC-142b, HCFC-22, and HCFC-22/HCFC-142b mixture were being used. However, conversion to these chemicals was generally still in the developmental phase. During 1994 the conversion to HCFC-141b accelerated in the US market. It is estimated that by the first of January, 1995 over 95% of the CFC-11 usage will have been converted to HCFCs so that the annual rate of use of HCFCs in refrigerator and freezer foam will grow to approximately 9,000 tonnes in that market. Over 95% of HCFC use is HCFC-141b. HCFCs are little used in the European market.

Table III-2. Estimated Global HCFC Consumption for Domestic Refrigerator and Freezer Insulation in 1993

Region	Tonnes 1993
North America	0
Western Europe	1,200
Eastern Europe	0
Middle East/Africa	0
Central/South America	0
Japan	100
Asia Pacific	100
Total World	1,400

Technical Options to Reduce Ozone Depleting Compounds

Current Options

Reduced ODP Options

Because the availability and performance characteristics of zero ODP options are inadequate to meet the needs of all markets, it is common practice (in some areas) to utilize options which reduce ODP as transition technologies until suitable zero ODP options are available.

Reduced CFC-11 technology is well proven, with use in Western Europe and elsewhere since 1989. This option allows immediate adoption in developing countries with little or no equipment modification. It is applicable where low or zero ODP materials are not readily available or implementable.

HCFC-141b has been proven in production and is now (1994) in wide use in the United States. It is also used to a significant extent in some other countries such as Japan. It

gives the best insulation value of any of the presently available alternative technologies. Energy consumption increase relative to CFC-11 foam is typically about 2 or 3% when comparing formulations using relatively high percentages of blowing agent (e.g. formulations used in North America). Care must be taken to prevent solvent attack by the HCFC-141b on plastic liners through selection of the liner materials, foam formulation and control of foam flow conditions. Generally, foam densities must be increased approximately 10% (relative to CFC-11 formulations) to provide adequate structural strength and optimum thermal conductivity. However, equipment modifications required to use this blowing agent are minimal. HCFC-141b is slightly flammable, and has a lower recommended occupational exposure limit than does CFC-11, so some added ventilation may be necessary.

HCFC-22 has been used as a replacement blowing agent by some companies which have "froth foaming" equipment. However, it has not been widely used because of the need for equipment changes, poorer energy performance than HCFC-141b, and questions about ageing rates.

HCFC-22/HCFC-142b mixtures have been used to some extent in Europe and Japan as a transitional technology. Energy consumption is degraded by 5% to 10% relative to CFC-11 foam. Equipment modifications are required in order to introduce liquified high pressure blowing agent to the polyol formulation.

Zero ODP Options

Because of the need to eventually phase out HCFCs, attention is now being focused on zero ODP options as the next generation blowing agent in all markets. Significant progress has been made. These materials are generally not yet fully proven, e.g. ageing and toxicological studies are incomplete, but some show considerable promise for the future. Current options include the following:

Hydrofluorocarbons (HFCs) have been extensively studied as potential alternatives to the HCFCs as replacement materials. They have the advantage of having zero ODP. Many are also non-flammable. Negatives include the fact that they may contribute to global warming.

The only HFC that has experienced significant use to date is **HFC-134a**. It has been used as a replacement blowing agent by a number of appliance manufacturers, mostly in Europe. It has a relatively high thermal conductivity and poor solubility in polyols. Together, these result in product energy consumption increases of up to 5% relative to "reduced CFC" foam products such as those used in Europe. Equipment modifications are required in order to handle the high pressure blowing agent. It is more compatible with plastic liners than is HCFC-141b. However, due to its inferior energy performance and the required equipment changes, it has not been used in markets with rigorous energy standards.

Hydrocarbons, most of which are readily available as bulk chemicals (although not necessarily in all markets in the purity required for appliance foam), have the advantage of being low cost and halogen free, with both zero ODP and near-zero GWP characteristics. However, hydrocarbons are flammable, have relatively high thermal conductivity, and contribute to the formation of ground-level ozone. There is also a need for development to qualify this technology for additional markets.

Cyclopentane has the lowest thermal conductivity of the pentanes. It is already being widely used in the appliance industry in Europe, and to some extent in Japan, Australia and some other countries. Much of the European industry has moved directly from "reduced CFC-11" formulations to cyclopentane, although many factories first converted to one of the other options. Attack on plastic liners is minor with this blowing agent. Therefore, little or no modification to materials is required. Density increases of about 10% (relative to CFC-11 foams) are required in order to provide a dimensionally stable foam.

From an energy consumption standpoint cyclopentane performs better than HFC-134a and other hydrocarbons. With current formulations there is an increase of up to 5% relative to European reduced CFC-11 and up to a 12% increase compared to US technology with higher levels of blowing agent. Switching from HCFC-141b to cyclopentane as a blowing agent and using current formulations would result in approximately a 10% increase in energy consumption for a typical North American refrigerator.

Handling hydrocarbons as blowing agents in the factory can be done safely if appropriate safety measures are applied. However, significant investment in plant modifications may be necessary, including provisions for improved ventilation, explosion-proofing, alarm systems, and scrubbing exhaust streams. The extent of plant modifications required may vary significantly, depending on local codes and regulations. For some foam products, burn test standards on finished products must be met, and in some cases the use of hydrocarbons may be limited by product safety requirements.

Long Term

All of the zero ODP options are long term alternatives as well.

Several liquid (at room temperature) HFCs are being studied as potential replacements for the HCFCs. These studies are concentrated on finding alternatives with energy and safety characteristics comparable to HCFC-141b. Several candidates, including isomers of **HFC-245**, **HFC-356**, and **HFC-365** are currently being evaluated. Non of these HFCs are commercially available, and even experimental quantities are difficult to secure.

Improved **pentane** technologies are being developed to reduce foam density and to reduce the increase in thermal conductivity with current formulations.

In the United States, the refrigerator/freezer industry, along with its suppliers, is conducting a coordinated program to evaluate the most promising candidates for the next generation blowing agent. A similar program is underway in Japan. Several HFCs are being considered, along with cyclopentane and will be evaluated to determine their performance, including insulation value and structural characteristics of the foam. In some markets, it may be necessary to conduct additional toxicological studies before determining that any of the candidates for next generation blowing agents can be approved for use in refrigerator/freezer foams.

Significant quantities of material are required in order to do all of the toxicity and application testing to qualify any new material as a substitute blowing agent. Also, suppliers require time to build manufacturing facilities to produce any new chemical after the decision to commercialize it has been made. Therefore, it is unlikely that commercial quantities of any of the new HFCs will be available until around the year 2000. Table III-3 summarizes the relative effectiveness of some candidate zero ODP blowing agents (relative to CFC-11) in foam insulation value.

Table III-3 Energy Performance of Blowing Agents

<u>Option</u>	<u>k-factor (@10°C)*</u> <u>(mW/m²k)</u>	<u>Increased Energy</u> <u>Consumption (%)</u>
CFC-11 (US)	16 - 18	0
CFC-11 (European)	18.5 - 19.5	8.5
Cyclopentane	19.5 - 20.5	12
HCFC-141b	17 - 18	2
HFC-356mff	19.0 - 20.2*	3.7
HFC-245fa**	18.0 - 18.5*	NA

* Some data are analytically extrapolated to 10°C from test results at 23°C to provide a comparison at a common temperature.

** Data for HFC-245fa is from "panels" and is not directly comparable to data for the other blowing agents (from sections cut from refrigerators).

NA: not available

Recovery/Recycling/Destruction

There is some activity (considerable in Europe) in attempting to recover or destroy blowing agents when disposing of appliances. Operations include dismantling and partial recovery of CFC-11 from the foam. Separation of the foam from the other materials is technically difficult. It is estimated that at least one-third of the CFC-11 is dissolved in the plastic matrix and cannot be recovered with available technology. Therefore, the most effective method to destroy CFC-11 in the existing stock of foam is to burn the foam in a suitably designed incinerator.

When considering recovery/recycling of products made with alternate blowing agents, there is some concern about safety issues when using equipment designed for non-flammable materials if flammable blowing agents are present.

Product Substitution

The most promising candidate for product substitution in the appliance foam area is the use of vacuum panels to replace, or partially replace, polyurethane foam. A variety of designs are currently under development. Generally they consist of a panel with an impermeable barrier/container enclosing a low-conductivity filler material under vacuum. Filler materials that have been used in panels which have been produced commercially include precipitated silica, perlite, diatomaceous earth, and fiberglass. Barriers have generally been made from laminated polymeric materials, frequently with metallic coatings or layers, or from thin sheets of stainless steel. Other technologies which are being investigated include ceramic spacers, aerogels, hydrogels, and open-cell rigid foam as filler materials, and glass as a barrier material. Vacuum requirements range from "soft" vacuums of approximately 50 mbar for aerogel tiles to "hard" vacuums of less than .001 mbar for ceramic spacers.

There has already been some movement to utilize vacuum panels as supplements to foam insulation in appliances. This has generally been done in order to achieve certain targets for energy consumption or to provide maximum storage space in a given size product. In the United States two manufacturers have used powder-filled flat vacuum panels in refrigerators, although relatively small production volumes were involved. Although these applications have been discontinued, development activity is continuing and one company has announced its intention to use larger quantities in the near future. In Europe there are three companies which reportedly produce at least one model containing vacuum panels. In Japan there is one company which currently produces products with vacuum panels. Another company had previously produced at least one model with powder-filled vacuum panels, but discontinued production due to high costs.

The energy consumption of refrigerators with vacuum panels varies, depending on such factors as the area of coverage, the effective thermal conductivity and thickness of the panels, the thickness of the product walls, and the quality of the foam surrounding the panels. Test results on products have varied from a savings of 25% on a freezer using a reduced CFC-11 foam in conjunction with the vacuum panels to a "break even" situation where a CO₂ blown foam was used in conjunction with vacuum panels, replacing CFC-11 blown foam in a refrigerator. In general, vacuum panels are more effective when applied to relatively thin-walled European-style cabinets than when applied to larger US models with thicker walls.

It should be noted, however, that the use of vacuum panels does not (with current design practices) significantly affect the amount or quality of the insulating foam required in a refrigerator or freezer. The volume occupied by the panels is relatively small, foam flow patterns and density are altered when using panels, and a high quality foam is required to avoid "edge effects" which would negate the value of the panels.

Conclusions

Several options exist to phase-out CFCs in rigid polyurethane foam for refrigerators and freezers. Many of these, including some zero-ODP options have now been implemented extensively in developed countries and are being implemented in some developing countries.

Factors which must be considered in choosing a blowing agent include energy consumption, safety (factory and customer), VOC emissions, product reliability, foam structural characteristics, cost, ozone depletion, and global warming. It is important that the next generation of blowing agents deliver the best overall performance in balancing these considerations. Some of the candidate HFC blowing agents have better thermal properties than cyclopentane, are not flammable, and are not VOCs. However, time will be required to allow adequate testing and development if they are to be given proper consideration.

OTHER APPLIANCES

Products and Applications

This category encompasses all "appliance" applications other than domestic refrigerators and freezers. The main applications are :

- Water Heaters -- Where foam insulation leads to a significant saving in energy consumption, particularly in designs where the space for insulation is limited.
- Commercial Refrigerators and Freezers -- Which are typically much larger than domestic units and includes open top display units.
- Picnic Boxes (Coolers) -- With a premium on insulation value and strong lightweight structures.
- Flasks and Thermoware -- Several types of articles require the same characteristics as picnic boxes.
- Refrigerated Containers (Reefers) -- A very stringent application with emphasis on durability and minimum wall thickness whilst maintaining insulation value.

Production Process

All the listed applications are produced by direct pour or injection of the foam chemicals between the inner and outer surfaces of the article. Most are held in moulds or jigs during the foaming process. Refrigerated containers are also produced by foaming section by section into a large pre-assembled jigged structure.

Global Consumption of CFCs in Other Appliances

Many producers in Europe and North America phased out of the use of CFC 11 during 1993. In developing countries, several producers are developing phase out plans. Consumption on a regional basis is given in Table III-4.

Table III-4. Estimated Global CFC Consumption for Other Appliances in 1993

Region	Tonnes 1993
North America	5,200
Western Europe	3,500
Eastern Europe	400
Middle East/Africa	200
Central/South America	200
Japan	800
Asia Pacific	2,100
Total World	12,400

Global Consumption of HCFCs in Other Appliances

Producers in North America, Western Europe and Japan are using a variety of HCFCs including HCFC-141b, HCFC-22 and the blend of HCFC-22/HCFC-142b.

Table III-5. Estimated Global HCFC Consumption for Other Appliances in 1993

Region	Tonnes 1993
North America	1,200
Western Europe	800
Eastern Europe	0
Middle East/Africa	0
Central/South America	0
Japan	0
Asia Pacific	100
Total World	2,100

Technical Options to Replace CFCs in Other Appliances

Current

Reduced CFC-11 Technology

Reduced CFC-11 formulations are suitable for all the applications and are a useful intermediate step in developing countries if a full replacement technology cannot readily be implemented. In most developed countries this technology has been replaced by HCFCs or another alternative.

HCFC-141b

This option has been chosen by several producers, particularly those manufacturing commercial refrigerators and freezers and refrigerated containers. This option offers the lowest thermal conductivity of any of the current alternatives and is particularly suited to these applications where internal volume is at a premium. Even so, there is an increase in thermal conductivity of up to 5% which is partly compensated for by improved foam structure/quality. For the lower density foams of about 30-32 kg/m³ density (with CFC 11) there is a need to increase density by up to 10% to ensure foam stability because of the softening effect of HCFC 141b on the foam matrix.

Plant modifications are generally not extensive since the flammability of HCFC 141b is only slight and are normally confined to ensuring adequate ventilation.

HCFC-22

This option has been used by a few producers and is particularly suitable for applications, such as thermoware, where the best possible insulation value is not of the greatest importance. Unless it is supplied in a pre-blended form, equipment modifications are necessary to introduce the blowing agent under pressure into the polyol formulation.

HCFC-22/HCFC-142b

This blend is suitable for all applications with the exception of refrigerated containers because thermal conductivity is too high. As with HCFC 22 equipment modifications may be necessary to introduce the blowing agent under pressure into the polyol formulation.

Pentane

Pentane isomers and cyclopentane are being used by some producers of water heaters and commercial appliances in Europe. Extensive plant, equipment and procedural modifications are necessary to ensure safe operations.

CO₂ (water blown)

Full CO₂ blowing is being used by some water heater producers where the space/thickness for insulation compensate for the loss of insulation efficiency which may be of the order of 50% over the lifetime of the product where gaseous diffusion can take place.

Long Term

Liquid HFCs

A series of HFCs which are liquid at ambient temperatures are being developed as candidate replacement for HCFCs. The main products are HFC 245 isomers, HFC 356 mff and HFC 365. In addition to toxicity the key parameter will be their cost effectiveness, in particular, the combination of their cost coupled with the thermal conductivity of the resulting foams. An additional issue is their global warming potential. It is unlikely that these products will be commercially available before about 2000.

Pentane

Pentane technology is still under development and it is likely that it will increase in importance as a zero ODP option.

CO₂ (water blown)

It is expected that improved CO₂ technology will be developed for this application in the longer term.

Recovery/Recycle/Destruction

Many of the same considerations applicable for domestic refrigerator and freezer appliances apply to this sector. There are considerable difficulties to separate the foam from the other materials used in the construction of the article. The most effective solution is to destroy the CFC (and the foam) in a suitably equipped incineration / energy recovery plant.

Conclusions

The producers and their suppliers have developed a variety of solutions to fully replace CFCs. Several of these are HCFCs and if all the attributes of the foams, particularly energy saving, are to be retained then sufficient time, up to about the year 2000, should be allowed to develop a range of effective replacements for all HCFCs.

CONSTRUCTION - BOARDSTOCK/FLEXIBLE-FACED LAMINATION

Products and Applications

Polyurethane (PUR) and polyisocyanurate (PIR) foam can be continuously laminated to various facing materials, such as aluminum foil, paper, glass roofing felts, and plasterboard. These products are primarily used as insulation in buildings, with some also used as tank and solar collector insulation.

In buildings, the largest use is in commercial roof insulation. Other uses include insulation for walls, cavities, internal linings (including agricultural buildings), exterior ventilated facades (Europe) and sheathing for residential construction (North America).

Rigid laminated PUR and PIR foams have penetrated many building insulation markets because these products offer the following properties:

- Low thermal conductivity -- High values of energy efficiency can be achieved by using comparatively thin layers of foam insulation. Laminated foams with impermeable facers offer the highest degree of long-term insulation value. The low thermal conductivity was originally derived from the fine, closed-cell polymer structure combined with CFC-11 as the main blowing agent. Retention of low thermal conductivity is a key concern when considering alternatives.
- Fire performance -- PIR and fire retarded PUR foams provide excellent fire test results under a variety of test procedures;
- Compressive strength -- This property is very important in roofing applications because of the construction and maintenance traffic that a roof system, including the insulation, must bear;
- Ease of processing -- One advantage of the product is its ease of manufacturing combined with its excellent adhesion to a whole range of facing materials; and,
- Ease of use and handling -- Laminated products are lightweight, offered in a variety of thicknesses, provide excellent structural rigidity, and, in the case of PIR

when used on roofs, can be sealed with hot bitumen and be used without separation technology.

Production Process

There are two principal types of continuous laminating machines:

- The continuous horizontal laminator used to produce products with two flexible facers, e.g., aluminum foil, paper or roofing felt; one flexible facer and one rigid facer; and,
- The inverse laminator variation used to produce one rigid facing in sheet form. The chemical components are metered and mixed from the mixing head onto the pressure conveyor where external heat may be applied to promote faster curing before the foam is moved to the cut-off saw area. This product can also be produced using slabstock production methods.

The two main centres of manufacture are Europe and North America. In Europe, mostly PUR foam is used with added fire retardant to obtain the desired fire properties and the term flexible faced lamination is commonly used. In North America, boardstock is a PIR product and no fire retardants are normally used. There is little production by this technique in developing countries.

Global Consumption of CFCs in Construction - Boardstock/Flexible-Faced Lamination

The estimated consumption of CFCs for lamination foams in 1993 compared to 1990 is shown in Table III-6. Several European producers switched out of CFC-11 beginning from 1992 and conversion will be completed by the end of 1994. North American manufacturers eliminated the use of CFCs by the end of 1993.

Table III-6. Estimated Global CFC Consumption for Construction - Boardstock/Flexible-Faced Foam in 1986, 1990 and 1993

Region	Tonnes 1986	Tonnes 1990	Tonnes 1993
North America	21,700	22,700	14,000
Western Europe	17,100	10,600	9,200
Eastern Europe	4,000	1,200	100
Middle East/Africa	1,800	100	800
Central/South America	0	600	0
Japan	2,600	2,600	600
Asia Pacific	3,800	500	0
Total World	51,000	38,300	24,700

Overall, CFCs have been used because of their ability to physically form the foam as well as to remain in the foam cells and provide good insulating performance. They are also used because they are inert chemicals which do not react with the other chemicals used to manufacture the foams. In addition, they are non-flammable, relatively non-toxic, efficient, and have suitable boiling points and have low solubility in the subsequent polyurethane polymer, but they do dissolve in and reduce the viscosity of the polyol component. Without CFCs in the production process, the high viscosity polyol component would make the blending, pumping, and production methods presently used extremely difficult to operate.

Global Consumption of HCFCs in Construction - Boardstock/Flexible-Faced Lamination

In the US, PIR boardstock switched to HCFC 141b or in some cases blends of HCFC-141b with small amounts of HCFC-22. HCFC-141b is the blowing agent which most closely matches the characteristics of CFC 11, especially in terms of thermal conductivity. In Europe, producers of flexible-faced laminate foams have chosen either iso or n-pentane or have preferred to use HCFC 141b for an interim period. In Japan, where overall production is much lower, HCFC 141b is the preferred option.

Table III-7. Estimated Global HCFC Consumption in Construction - Boardstock/Flexible-Faced Lamination Foam in 1993

Region	Tonnes 1993
North America	6,500
Western Europe	1,500
Eastern Europe	0
Middle East/Africa	0
Central/South America	0
Japan	500
Asia Pacific	0
Total World	8,500

Options to Replace CFCs in Construction-Boardstock/Flexible-Faced Lamination

Current

HCFC-141b

This option is in use by all US producers, in Japan and by many European producers. It offers most of the advantages of CFC 11. However, the higher conductivity of the gas may give an increase in both initial and aged thermal conductivity up to 5% compared to CFC 11-based foams. In addition, an increase in foam density up to 10% may be necessary to ensure that the product is dimensionally stable.

Pentane

The n and iso isomers of pentane have been used in several European countries starting in 1992 to answer a demand for zero ODP products. More recently there has been some minor use of cyclopentane. Their use entails extensive modifications to the production equipment and the factory area plus suitable operating procedures because of the highly flammable nature of pentane.

Relative to European CFC reduced formulations the thermal conductivity is increased by up to 10%, both initial and aged. The result is that some important product categories cannot be produced.

Most European fire codes can be met but with major increases in fire retardant levels. This results in a net cost increase despite the lower cost of the n and iso isomers compared to CFC-11. Large scale fire tests with these products have shown comparable behaviour to CFC 11-based products.

Evaluations of this option in US boardstock systems shows that all required fire tests cannot, as yet, be met by current technology.

Pentane is also a VOC and its use in several countries, particularly the US, could be inhibited.

Previously Considered Options

Reduced CFC-11

This technology was used for an interim period both in Europe and North America.

HCFC-22/HCFC-142b blends

These options, although evaluated, were not adopted as HCFC-141b and the pentane isomers were preferred.

CO₂ (water blown)

There has been some minor production with 100% CO₂ (water) blowing but the predicted deficiency of an increase in aged thermal conductivity of more than 50% and a density increase of about 15% showed that current technology is not viable.

Long Term

Liquid HFCs

A series of HFCs which are liquid at ambient temperatures are being developed as candidate zero ODP replacements for HCFC-141b. The main products are HFC-245 isomers, HFC-356 mffm and HFC-365. In addition to toxicity the key parameter will be their cost effectiveness, in particular, the combination of their cost coupled with the thermal conductivity of the resulting foams. An additional issue is their global warming potential. It is unlikely that these products will be commercially available before about 2000.

Pentane

The applicability of this option may increase with further development, particularly with respect to the flammability performance versus US fire codes and initial thermal conductivity.

Recovery/Recycle/Destruction

Extensive studies have shown that in an aged foam about one third of the CFC-11 is dissolved in the plastic matrix. This means that it is not technically feasible to recover this fraction even if the balance could be recovered for recycling by a technique such as crushing the foam to break the cells.

Consequently, the most effective method to destroy the CFC-11 in the existing stock of foam is to burn the foam in a suitably equipped incinerator which can convert the calorific value of the foam into energy.

In practise, the foam product could not be separated from other building materials such as felt. This reinforces the choice of incineration/energy recovery as the best option.

Product Substitution

Many other products are currently available for use as building insulation materials. These products include expanded polystyrene, fibreboard, fibrous glass (mineral fibre) and cellular glass and have always competed for market shares with PUR and PIR products.

It is extremely difficult to predict the likely movements in market shares arising from the change to CFC-free formulations since there are other equally germane issues affecting product selection.

Direct substitution of foams is specifically difficult because, when a substitution is made, the alternative material will have a higher thermal conductivity (lower insulation value) per unit thickness.

Additional difficulties exist in building and industrial applications where there is a need for waterproof characteristics, building code compliance and insurance requirements, combustibility requirements, or building design constraints. In these instances, it is not always easy to substitute directly. If a substitution was made, it would require considerable changes in design and construction practice which will result in an increase in construction cost.

Substitute insulation products may become more competitive if the choice of alternative blowing agent reduces the thermal conductivity or substantially increases the cost of the foam insulation.

Conclusions

The producers have mostly replaced CFCs in their products and the most commonly used alternatives are HCFC-141b and the pentane isomers. Replacements for HCFC-141b such as liquid HFCs are under development and, coupled with refined technology based on pentane isomers, are expected to be available by the year 2000. If phaseout schedules for HCFCs are accelerated much beyond the current timetable there is likely to be a considerable environmental penalty in energy consumption.

The most effective means of disposing of CFCs in foam is by incineration / energy recovery.

CONSTRUCTION AND TRANSPORT: SANDWICH PANELS

Products and Applications

Sandwich panels have foam cores between rigid facings. The facings are often profiled to increase rigidity. Facing materials are typically steel, aluminum or glass fiber reinforced plastic sheet.

The panels are increasingly being used in the construction industry for applications such as:

- cold stores: for frozen and fresh food storage;
- doors: entrance and garage;
- retail stores: including the cold rooms for food storage within them; and
- factories: particularly where hygienic and controlled environments are required such as in electronics, pharmaceuticals, and food processing.

The panels are also used in the transport industry for the manufacture of insulated trucks and reefers.

In all applications, the insulating property of the foam is used in conjunction with its strength and self-adhesive capability. The panels are components of high quality modular construction techniques and their use is growing rapidly in developed and developing countries.

Production Processes

The panel thickness, depending on application, varies from 30 to 200 mm and products over the entire range can be made by either continuous or discontinuous processes.

Continuous Process

The continuous process uses a horizontal laminator similar to that used for the production of boardstock/flexible-faced laminates. However, additional equipment is installed to convert coiled sheet steel to profiled facings which are fed into the laminator.

Discontinuous Process

In the discontinuous process, pre-profiled or flat facings are assembled, with appropriate spacers, in single- or multi-daylight or in oyster presses. The foam is injected at multiple ports or a lance withdrawal technique is used.

Global Consumption of CFCs in Construction and Transport - Sandwich Panels

Many producers in Europe and North America switched out of using CFC-11 during the course of 1993 and will complete the conversion during the course of 1994. Producers in developing countries are generally at the stage of formulating their phaseout plans. The estimated consumption of CFCs for sandwich panels in 1993 was 18,800 compared to 24,100 tonnes used in 1990. Consumption on a regional basis is provided in Table III-8.

Table III-8. Estimated Global CFC Consumption for Sandwich Panels in 1990 and 1993

Region	Tonnes 1990	Tonnes 1993
North America	5,900	3,200
Western Europe	9,500	9,900
Eastern Europe	1,600	600
Middle East/Africa	800	1,100
Central/South America	500	800
Japan	3,800	400
Asia Pacific	2,000	2,800
Total World	24,100	18,800

Global Consumption of HCFCs in Construction and Transport - Sandwich Panels

Although total HCFC consumption is low, producers are switching into a variety of replacements including HCFC-141b, HCFC-22/HFC-142b blends and HCFC-22. There is a comparatively minor usage of pentane isomers in Europe.

Table III-9. Estimated Global HCFC Consumption for Sandwich Panels in 1993

Region	Tonnes 1993
North America	3,400
Western Europe	2,800
Eastern Europe	0
Middle East/Africa	100
Central/South America	0
Japan	200
Asia Pacific	0
Total World	6,500

Technical Options to Replace CFC Consumption

Current

Reduced CFC Technology

Reduced CFC 11 formulations have been used as an interim stage by several producers but mostly have been superseded by CFC-free options in developed countries. Some developing country producers have also adopted this technology as an intermediate step.

Product characteristics are retained except for an increase in thermal conductivity of about 5%.

HCFC-141b

This option has been chosen by most producers. The product characteristics have been fully maintained. An increase in foam density has been required in some cases, particularly in instances where the core density is less than 40 kg/m³, to offset the softening effect of HCFC 141b on the foam matrix.

The plant modifications are generally not extensive and are usually confined to ensuring that ventilation is adequate. The foam formulations have been modified to satisfy national fire codes.

HCFC-22

Some producers, using both continuous and discontinuous techniques, have used this option since 1992. Equipment modifications are necessary to introduce the blowing agent as a liquid, under pressure, into the polyol formulation.

Because of the impermeable nature of the generally steel facers, the comparatively rapid diffusion of HCFC-22 out of the foam matrix does not cause a problem for most applications.

HCFC-22/HCFC-142b

This option is used by several manufacturers using both continuous and discontinuous production methods. As with HCFC-22, a pressurised introduction system is necessary with this low boiling blowing agent blend.

The use of the blend ratio 40:60 HCFC-22:HCFC-142b eliminates the flammable nature of HCFC-142b whilst its presence compensates for the comparatively rapid diffusion of HCFC-22.

Pentane

Some producers in Europe are switching to the n or iso isomers or to cyclopentane to obtain a zero ODP product. Their use may result in an increase of thermal conductivity of up to 5 percent. Extensive and expensive modifications are required to the equipment factory area and operating procedures because of the highly flammable nature. Formulations also have to be adjusted to meet applicable fire codes.

In addition, pentane is a VOC and its wide scale use may be limited.

HFC-134a

Formulations based on HFC 134a are in use for the production of sandwich panels by the discontinuous technique. The formulations can be supplied in a pre-blended form which obviates the need for modifications to add it as a liquid under pressure to the polyol formulations. There is a thermal conductivity increase of about 10% compared to CFC 11-based foams.

CO₂ (water blown)

There is minor use of this option, particularly in applications where optimum thermal insulation is not a high priority.

Long Term

Liquid HFCs

A series of HFCs which are liquid at ambient temperatures are being developed as candidate replacement for HCFCs. The main products are HFC 245 isomers, HFC-356mff and HFC-365. In addition to toxicity the key parameter will be their cost effectiveness, in particular, the combination of their cost coupled with the thermal conductivity of the resulting foams. An additional issue is their global warming potential. It is unlikely that these products will be commercially available before about 2000.

Pentane

Pentane technology is still under development and it is likely that it will increase in importance as a zero ODP option.

CO₂ (water blown)

It is expected that improved CO₂ technology will be developed in the longer term for such applications as doors.

Recovery/Recycle/Destruction

As with boardstock/flexible-faced lamination, it is not technically feasible to recover and then recycle all the CFC-11 from the existing stock of foams. After separating the foam from the rigid and generally non-combustible facers, the most effective method to destroy the CFC-11 is to burn the foam in a suitably equipped incinerator which can convert the calorific value of the foam into energy.

Product Substitution

Many of the considerations listed for boardstock/flexible-faced laminates are equally applicable for sandwich panels. However, direct substitution of polyurethane foam in structural applications is less likely since the polyurethane foam contributes significantly to the overall properties of the panel in a manner which fibrous products, for example, cannot match.

Conclusions

The producers have mostly replaced CFCs in their products and the most commonly used alternatives are HCFC-141b and HCFC-22/HCFC-142b and the pentane isomers. Replacements for HCFC-141b and HCFC-22/HCFC-142b such as liquid HFCs are under development and, coupled with refined technology based on CO₂ (water), pentane isomers and HFC-134a, are expected to be available by about the year 2000. If phaseout schedules for HCFCs are

accelerated much beyond the current timetable there is likely to be a considerable environmental penalty in energy consumption.

The most effective means of disposing of CFCs is by incineration/energy recovery.

SPRAY POLYURETHANE FOAM INSULATION

Products and Applications

Sprayed foams are used for in situ application of rigid thermal insulation. Their major use is in roofing applications, especially in North America. Worldwide, sprayed foams are used for residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailers and tanks. Spray foam is applied by contractors in the field in accordance with the instructions of manufacturers of spray foam systems.

Production Process

Spray foam is applied using a hand-held pressurized spray gun, in which separate polyol and isocyanate liquids are metered under pressure, mixed and then dispensed. Different formulations or processing parameters impart specific properties to the foam, such as increased compressive strength, good dimensional stability at high heat and humidity, and greater high temperature stability. The ability of the formulator to adjust foam properties is beneficial, considering the foam is applied in a variety of climatic conditions.

The foam is sprayed directly from the mixing head onto the substrate. This method of application facilitates coverage of large and complex surfaces. For those applications where a thick layer of foam is needed, multiple thin layers of foam, of not less than 10 mm, are applied to create the thick layer. The sprayed foam needs to be highly reactive, especially for adhesion to vertical surfaces during application. Pipes can also be insulated with spray foam by using a fixed spray gun and rotating and traversing the pipe.

Global Consumption of CFCs in Spray Foam

Several users switched away from CFC-11 during 1993. The estimated consumption of CFCs for spray foams in 1993 was 11,000 tonnes compared with 12,800 tonnes used in 1990. Consumption on a regional basis is provided in Table III-10.

Table III-10. Estimated Global CFC Consumption for Spray Foam in 1990 and 1993

Region	Tonnes 1990	Tonnes 1993
North America	6,000	4,100
Western Europe	1,500	1,900
Eastern Europe	500	100
Middle East/Africa	500	1,200
Central/South America	500	100
Japan	2,300	2,400
Asia Pacific	1,500	1,200
Total World	12,800	11,000

Global Consumption of HCFCs in Spray Foam

Several users switched to HCFC-141b during 1993, but the biggest transition year was 1994.

Table III-11. Estimated Global HCFC Consumption for Spray Foam in 1993

Region	Tonnes 1993
North America	800
Western Europe	200
Eastern Europe	0
Middle East/Africa	0
Central/South America	0
Japan	1,300
Asia Pacific	0
Total World	2,300

Technical Options to Reduce CFC Consumption

Current

HCFC-141b

HCFC-141b is a proven technology in wide use. In most instances, this is combined with small amounts of water to generate CO₂. The benefits of CFC 11-based spray foam are retained. No machinery modifications are required.

CO₂ (water blown)

One hundred percent CO₂ blowing is a proven technology but is not in wide use because of the increase in thermal conductivity of the foam. Currently, the mechanical properties of foam blown with 100% CO₂ are similar to those based on CFC-11. Thermal conductivity has increased by 20-25% in initial value to more than 50% in aged value. Foam density has to be increased by 20-30%.

Long Term

A series of HFCs, which are liquid at ambient temperatures, are being developed as candidate replacements for HCFCs. These include isomers of HFC-245, HFC-356 and HFC-365. Issues include toxicity, global warming potential and cost effectiveness, in particular, cost combined with thermal conductivity of the resulting foams. All evaluations are at an early stage and these products will not be commercially available before about 2000. Hydrocarbons may not be a viable choice for spray foam due to flammability concerns. As a result, future developments for spray foam may go in the direction of CO₂ or water based foams due to the projected cost of HFCs.

Conclusions

Due to the requirements of spray foams, HCFC-141b is the key alternate at least until about the year 2000. All evaluations of HFCs are in the early stages and foams blown with 100% CO₂ have an initial increase in thermal conductivity of 20-25%.

OTHER RIGID POLYURETHANE FOAM APPLICATIONS

Other rigid polyurethane foam applications include slabstock, pipe-in-pipe, and one component foams.

In this section, Global Consumption could not be broken out by individual application and is, therefore, shown at the end of this section.

Slabstock

Product Applications

Rigid polyurethane slabstock is used as insulation for pipes and storage tanks, as insulation boards in construction, and can be the insulating material for refrigerated transport containers. Rigid slabstock can be fabricated into a variety of product shapes and forms.

Production Process

Rigid slabstock is produced using either the discontinuous or the continuous manufacturing process. Traditionally, CFC-11 has served in both processes as the blowing agent, although water and/or CFC-12 are sometimes incorporated into the foam mixture. During 1993, partial conversion to alternate blowing agents took place.

Discontinuous Process

In the discontinuous method, the chemical components of a slow-reacting foam system are weighed and hand or machine-mixed, after which they are poured into a wooden or cardboard mould. Fitted on top of the foam, a floating lid rises with the expansion of the foam. The lid serves to level the top surface of the foam block that is being produced. The output of the discontinuous method can be increased by using mechanical stirrers and agitators to replace the hand-mixing stage, or by machines that both mix and dispense the foam reaction mixture into the mould.

Continuous Process

In the continuous process, the foam reaction mixture is dispensed continuously into a trough lined with paper or polyethylene film and located on a moving conveyor belt. The foam expands as it moves forward on the conveyor belt. Some belts are fitted with equipment that produces a foam with a flat top surface, similar to the floating lid used in the discontinuous process.

In production by either method, the foam rises due to the expansion of the blowing agent and cures. Then it is cut into sections for use in the applications and products listed above. In general, rigid slabstock has neither a facer nor an impermeable liner attached to it.

Technical Options for Reducing CFC Consumption

Current

Immediate and short term options for slabstock are very similar to those for flexible-faced laminates/boardstock.

Reduced CFC-11 Technology

Reducing the amount of CFC-11 in the foam formulation is feasible and has been introduced by some slabstock producers. However the higher exotherm is a critical problem in slabstock foams and limits the reductions which can be achieved.

In addition, an increase in the thermal conductivity of the foam, up to 10%, may occur when using reduced CFC-11 formulations and their long-term thermal ageing characteristics may be negatively affected.

HCFC-141b

HCFC-141b is widely used by both the continuous and discontinuous slabstock producers. The resulting foams exhibit properties which are very similar to those based on CFC-11 and have the best thermal properties. North American producers converted totally to HCFC-141b.

Pentanes

In Europe some percentage of the slabstock production was converted to n-, iso-, or cyclopentane as blowing agent, especially in countries or markets where HCFC-141b is considered environmentally unacceptable. Cyclopentane is used in cases where thermal insulation properties are specified by government codes because c-pentane yields the highest insulation values of the pentanes.

Safety precautions are necessary for the production, foam storage area and for foam fabrication due to the flammability characteristics of pentane.

Work is still in progress to develop formulations for highly combustion resistant foams.

Long Term

A range of liquid HFCs are being developed for commercialisation later in the decade. These include isomers of HFC 245, HFC 356 and HFC 365. Issues which must be resolved include toxicity and potential environmental effects such as global warming. All evaluations are at an early phase. Where open-celled foam is an acceptable product improved all CO₂ (water) blown foam formulations may represent an option.

Conclusions

The use of pentane will require major capital investment in safety-related improvements which may be difficult to justify for small, discontinuous slabstock producers.

Open-celled, CO₂ (water) blown foams may be an option where thermal insulation is of lesser concern, but further process development is required. These foam will not be acceptable for all current applications.

PIPE-IN-PIPE/PREFORMED PIPE

Products and Applications

Foam-insulated pipe-in-pipe sections typically have an inner steel pipe which is surrounded with foam insulation which, in turn, is protected by a plastic outer skin. These pipes are installed underground and are used to transport hot water from a central boiler to surrounding dwellings. Similar pipes and others insulated with preformed pipe sections are used in production units and chemical plants for the transport of hot or cold fluids. Large diameter insulated pipes may have post-applied elastomeric or bituminous coatings to provide a permanent water barrier.

Production Processes

Pipe-in-pipe sections are produced by injecting the foam chemicals into the cavity between the inner and outer pipes. Preformed pipes are produced by pouring or injecting the foam chemicals into half-section moulds.

Continuous processes have been introduced in which the foam is injected onto the inner pipe, cured and the outer plastic cover is then extruded onto the foam through an annular die.

Technical Options to Reduce CFC Consumption

Current

CO₂ (water blown)

Several European pipe-in-pipe producers converted some portion of their product line to all CO₂ (water blown) technology. Key considerations for this option include:

- The pipe-in-pipe construction minimises ageing of the foam thermal conductivity; and,
- A zero ODP option was preferred or required in Scandinavia, which has a significant share of the world market for this application.

Appropriate certifications for these products were obtained. Other portions of this market, however, required better thermal insulation values and/or physical properties, which could not be achieved with all CO₂ (water blown) foam.

HCFC-141b

HCFC-141b is in use in Europe and especially in North America for this application and offers the highest thermal insulation values.

Cyclopentane

Latest developments have shown that cyclopentane can be used in this application and some European companies have introduced pipe-in-pipe products or are shortly doing so. Insulation values are reported to be comparable to HCFC-141b blown foams in this application.

A modification of this technology is the use of a hydrocarbon/noble gas blend.

Long Term

Further development work and capital investment will be required for the widespread acceptance of pentanes.

CO₂ (water) technology will be a viable alternative in the pipe-in-pipe market, provided further improvements will be made.

No development efforts for HFCs are currently known.

Conclusions

The large scale industrial production of pipe-in-pipe insulation in few production sites will make it likely that pentanes will become the preferred blowing agents. HCFC-141b may be replaced before the year 1998.

Producers who select CO₂ (water) as the blowing agent must make system design changes to compensate for the inherently lower insulation value.

ONE COMPONENT POLYURETHANE FOAM

Products and Applications

One component foams are used by both the building industry and the do-it-yourself market in a variety of applications. These include draft-proofing around pipes, cable runs, doors, and windows; sealing doors and window frames; and joining insulating panels, roofing boards, and pipe insulation. One component foams are preferred because they are portable and easy to apply, and offer both thermal and sound insulation properties.

Production Process

One component foams are polymeric MDI-based prepolymer compositions that historically contained dissolved CFC-12. CFC-12, which has a lower boiling point than CFC-11, has been used because it acts as a propellant and because it produced "frothed" foam, thereby preventing the material from flowing away from the site of its application. Additionally, one component foams do not generate enough heat to volatilise CFC-11.

One component foams are supplied in pressurized cylinders and aerosol cans fitted with a nozzle through which a thin strip of material is extruded. After application, the foam expands at room temperature and cures by reacting with moisture in the air. This characteristic is unique to one component foams. The foam continues to cure internally after becoming dry to the touch as moisture from the air diffuses into the foam. The total time needed for foam cure depends on temperature and relative humidity.

Technical Options to Reduce CFC Consumption

Current

HCFC-22 or HCFC-22/HCFC-142b blends

HCFC-22 or HCFC-22/HCFC-142b blends can produce one component foam with characteristics similar to foams containing CFC-12. Manufacturers have introduced these blends into product formulations.

Propane or Butane

Hydrocarbons, such as butane or propane, have been introduced by many one component foam manufacturers because they have zero ODP. Changes were required in the foam packaging plants because of the flammability of the blowing agent/propellant.

Dimethyl Ether (DME)

DME is currently being used as the sole blowing agent or in combination with the above. However, its flammability also may require changes of the filling equipment and plants.

Long Term

Hydrocarbons, possibly in combination with DME, will also be long-term alternatives. HFC-152a will be evaluated but formulation changes are required to accommodate this HFC. Water to generate CO₂ cannot be used in this application.

Conclusions

The need for intermediate and long-term strategies depend more on application needs and product characteristics than on environmental issues, because of the availability of zero ODP options.

The search for long-term options will be dictated by blowing agent solubility characteristics. Prospective replacements can include many low boiling compounds, such as HFC-152a.

Global Consumption of CFCs in Other Rigid Polyurethane Foam Applications

The estimated consumption of CFCs for other rigid polyurethane foams was 7,000 tonnes compared with 11,300 tonnes in 1990. Consumption on a regional basis is provided in Table III-12. The data are reported in aggregate for all sub-sectors (i.e., slabstock, pipe-in-pipe, and one component foam) because data for the individual applications are not available. For slabstock significant reductions in use of CFC-11 occurred in 1993. Several European manufacturers have completed the switch away from CFC-11 for pipe-in-pipe. Most European manufacturers no longer use CFC-12, following national regulations in several countries, especially for one component foam. In North America, the conversion was generally to HCFC-141b for slabstock and pipe insulation and to hydrocarbons and dimethyl ether (DME) for one component foams.

Table III-12. Estimated Global CFC Consumption for Other Rigid Polyurethane Foam Applications in 1990 and 1993

Region	Tonnes 1990	Tonnes 1993
North America	1,300	2,000
Western Europe	7,700	2,500
Eastern Europe	1,000	300
Middle East/Africa	200	200
Central/South America	200	100
Japan	400	0
Asia Pacific	500	1,900
Total World	11,300	7,000

Global Consumption of HCFCs in Other Rigid Polyurethane Foam Applications

Table III-13. Estimated Global HCFC Consumption for Other Rigid Polyurethane Foam Applications in 1993

Region	Tonnes 1993
North America	800
Western Europe	1,000
Eastern Europe	0
Middle East/Africa	0
Central/South America	0
Japan	0
Asia Pacific	0
Total World	1,800

FLEXIBLE POLYURETHANE FOAMS

Products and Applications

Slabstock Foams

Polyurethane flexible slabstock foams include both polyether and polyester-based foams used to produce foam cushioning products of varying densities and firmness, in each of the generic categories; conventional, high-resilience (HR), and combustion modified high resilience (CMHR).

Slabstock foams are widely used in furniture, bedding, carpet underlay, and automotive interiors (both cushioning and sound dampening). Many specialty foams are used for technical applications such as air filters, fuel cells, and anti-static packaging. Available in a range of densities and firmness, the foams are produced in large blocks which are cut for use in individual application.

In applications requiring combustion modified foams to meet fire safety standards, the foams include melamine, graphite, chlorinated phosphoric esters, or alumina trihydrate to improve the foam's flammability performance. Greater amounts of auxiliary blowing agents are normally used in these foams to offset the increased hardness and density resulting from the introduction of these solid additives.

Combustion modified foams are mainly used in upholstered furniture and bedding applications. In some countries, they are used principally in prisons, institutions and mass transit; however, in other countries, such as the UK, their use is compulsory for all domestic applications of upholstered furniture and bedding. Most of the technical options available for flexible slabstock foams can be used in combustion modified foams as well, except where noted.

Moulded Foams

The most significant use of flexible moulded polyurethane foam is in the automotive field for seat cushions, back cushions, armrests, and headrests. Flexible moulded foams are used in seating applications for other transportation, such as trains, buses, and airplanes. A specialty market is the sound dampening in cars by backfoaming of the carpet and/or firewall insulators (shared with slabstock). Together, these uses account for at least 90% of the flexible moulded foams used worldwide. The other 10 percent of moulded foams is used for non-automotive or furniture applications.

Production Process

Continuous Processes

Traditional Slabstock Method

In a typical continuous slabstock foam production line, the slabstock foam is produced on an enclosed continuous conveyor belt, called a "foam tunnel", that can be over 60 metres long.

Liquid chemicals are metered to a mixing head. Feed formulation varies for different foam grades and between different foam producers.

The metered stream from the mixing head is dispensed to a nozzle with a traversing pattern across the width of the initial inclined portion of the conveyor belt: this is termed the "lay down". The conveyor belt is lined with paper or polyethylene film to make a "U" shaped retainer for the rising foam mass as it descends the slope.

As the polymerisation reactions proceed and cells form, the foam rises and the blowing agents are volatilised due to internal heat generation. Within six metres of the lay down, the foam mass generally reaches its point of maximum expansion.

The foam can be as high as 1 to 1.25 metres and up to 2.5 metres wide. From its maximum expansion, the foam starts to release its blowing agents and some unreacted chemicals. A ventilated tunnel, typically covering the first section of the conveyor system, exhausts these emissions and thereby controls workplace concentrations.

The continuous slab of foam moves through the production tunnel to a cut-off saw which slices it into blocks for curing and storage. These blocks can be as short as 1 meter or as

long as 60 metres. The exothermic chemical reaction continues within the foam mass while in the curing area. The natural insulating qualities of the foam maintain the heat for a period of several hours. Slowly, the heat dissipates while air penetrates the block and replaces the blowing agent.

The traditional traversing slabstock process is less economical than newer methods; consequently, the use of this process is on the decline. In addition, processing is generally more critical, and the introduction of CFC alternatives is more problematic. However, the process is still the primary choice for polyester foams and many other specialty products where cell size and cell uniformity are critical.

Maxfoam/Varimax

Developed in the early 1970s, the Maxfoam/Varimax process differs from the traditional method in lay down and foam expansion. The metering from the mixing head is discharged directly into the bottom of a trough, which is nearly level with the ultimate height of the foam slab.

The rising foam mass expands and spills over the front edge of the trough and is drawn away on a series of sloped fall plates. This slope is kept similar in shape to the rise profile of the foam, thus allowing a downward expansion, giving the resulting foam slab a nearly rectangular shape.

Currently the process of choice for most manufacturers, the Maxfoam/Varimax process for flexible foam production is less complicated and more efficient than conventional foaming (higher blocks, more density control and firmness control).

Vertifoam

The Vertifoam process produces foam vertically rather than horizontally. This results in full-sized blocks at a far lower foam chemical throughput rate and a slower production rate than conventional equipment. This more controllable rate is suited to small to medium manufacturers, since it allows efficient operation from 500 to 3,000 tonnes per year.

In addition, the foam blocks produced are accurately shaped and trimming losses are low. All the skins on Vertifoam blocks are thinner and less dense than conventional blocks and have none of the heavy top and bottom skin. These thin skins allow rapid diffusion for cooling or recovery. Both square blocks and round blocks can be produced.

The Vertifoam process differs substantially from conventional horizontal foam machines that need high chemical throughput rates to produce large foam blocks. The high chemical throughput rates of conventional foam machines result in high capital costs and large heating and ventilation requirements.

The reductions in floor area achieved with the Vertifoam process are very substantial -- up to 85% reduction has been reported. The lower chemical throughput of the process means that a large reduction in the extraction system is possible, which in turn means heating and ventilation costs are reduced.

In countries where legislation may in the future require blowing agent recovery and/or fume scrubbing, the low air extraction rate substantially reduces the capital and running costs of recycling and/or scrubbing equipment.

Discontinuous Processes

Box Foam

In many developing countries where manpower is abundant, two pre-batched liquid components are mixed together and then literally poured into a lined box, which then expands and cures into a final block.

Moulded Foams

In the production of moulded flexible foams, chemicals are dispensed (usually a pre-blended two component system) to an open mould of a desired shape and size. Following mould cleaning and application of a release agent, the moulds are filled, sometimes manually, and then closed.

As the foam reactions occur within the mould, the polymer forms and simultaneously expands to fill the mould cavity. Many moulded products are manually flexed and/or crushed by rollers upon removal from the mould, which opens the remaining cells. In some cases, the newly-demoulded part is heat-treated to further cure and harden the skin.

Generally, within the automotive field, flexible moulded foam can be produced by either "hot cure" (approximately one third of production) or "cold cure" (approximately two-thirds of production) on a worldwide basis. Hot cure foam production is used exclusively for automotive seating and headrests. Cold cure moulded foams are used in both automotive (seating, headrests, carpet ticking backing) and non-automotive (furniture) uses.

CFC-11 has typically been used in supersoft grades (for back cushions) and in the low-density grades (25 kg/m³). In 1986, approximately 10% of all moulded foam production used CFC-11 in manufacture. In formulations using high resilience foam, auxiliary blowing agents are essentially phased out.

Global Consumption of CFCs and HCFCs in Flexible Polyurethane Foam

Slabstock Foam CFC Consumption

Approximately 46,750 tonnes of CFC-11 was used worldwide in 1986 in the production of flexible slabstock foam. At the time, this figure represented 17% to 18% of all CFCs used in the production of plastic products. The use of CFC-11 in the production of flexible foams has declined substantially worldwide since 1986. The estimated consumption of CFC's for flexible polyurethane slabstock had dropped to 12,450 tonnes in 1990 and 9,250 tonnes in 1993.

The complete elimination of CFCs in flexible foams has already been achieved in North America and will also be eliminated in Western Europe by Jan 1, 1995. There has been tremendous marketing/consumer pressure on the flex foam industry to supply and promote the product as "CFC-Free".

Moulded Foam CFC Consumption

In 1986, approximately 13,700 tonnes of CFC-11 were used in the production of flexible moulded foam worldwide. In 1990, it was estimated that 1,500 tonnes were used. In 1993, consumption had dropped to approximately 550 tonnes (mostly in Egypt, India, Indonesia, Malaysia, China, the Philippines, and Argentina).

There has been a trend towards using less CFC-11 in moulded foam applications as automobile manufacturers increase densities of the foam seats. In moulded foams, however, the CFCs are used not only for density reduction, but also for flowability of the foam system in the moulds.

Table III-14. Estimated Global CFC Consumption in Flexible Polyurethane Foam in 1986, 1990 and 1993

Region	Tonnes 1986	Tonnes 1990	Tonnes 1993
Slabstock			
North America	11,150	1,350	25
Western Europe	10,800	5,900	3,000
Eastern Europe	4,400	800	1,600
Middle East/Africa	6,200	1,200	225
Central/South America	5,300	1,000	500
Japan	2,000	900	100
Asia Pacific	6,900	1,300	3,250
Total Slabstock	46,750	12,450	8,700
Total Moulded	<u>13,700</u>	<u>1,500</u>	<u>550</u>
Total World	60,450	13,950	9,250

Table III-15. Estimated Global HCFC Consumption for Flexible Polyurethane Foam in 1993

Region	Tonnes 1993
Slabstock	
North America	110
Western Europe	100
Eastern Europe	50
Middle East/Africa	0
Central/South America	0
Japan	10
Asia Pacific	0
Total Slabstock	270
Total Moulded	0
Total World	270

Technical Options to Reduce CFC Consumption

The flexible foam industry and its suppliers have been for more than seven years involved in efforts to reduce or to eliminate the use of CFCs in their manufacturing processes.

A flood of technologies have been proposed over these years, allowing the industry to make significant progress in the phase-out of CFCs. Today, the use of CFCs in flexible PUR has been virtually eliminated in developed countries and many developing countries have made great strides towards the same goal. The first projects completed through the Multilateral Fund (MLF) of the Montreal Protocol, a fund that financially supports ODS phaseout in eligible developing countries, have been flexible foam operations.

In general, the following standards of acceptance are applied to proposed replacement technologies:

- proven technology,
- commercially available,
- acceptable processing,
- sufficiently safe,
- environmentally acceptable,
- economically viable.

The standard blowing agent for flexible polyurethane foam is carbon dioxide, generated from the reaction between water and toluene diisocyanate (TDI). Auxiliary blowing agents (ABAs) are used because there are limits on the foam properties that can be achieved with chemically generated carbon dioxide as the sole blowing agent and because of the exothermic nature of the water/TDI reaction. Excessive heat can lead to scorch or even auto-ignition of the foam during the manufacturing process and subsequent curing.

The uses of ABAs are to:

- soften the foam
- decrease the reaction temperature,
- decrease the foam density.

CFCs have for years functioned as the ABAs of choice. In view of the function of an ABA, it is clear that an ideal alternative should allow for the same or better

- hardness variations,
- decrease of the exotherm,
- density range.

Traditionally, densities of molded foams have been higher than slabstock foams, reducing the function of ABAs in molding to softening alone. This has greatly facilitated the application of CFC-free options, and substantially eliminated the use of ABAs in this category throughout the world.

Options to reduce/eliminate CFCs in flexible PUF can be categorized as follows:

- conservation,
- alternative blowing agents,
- chemical modifications,
- alternative manufacturing technologies,
- product substitution (not-in-kind).

Conservation

Conservation techniques are those technologies and procedures, understood to reduce the use of CFCs through best management practices, reformulation and recovery/recycling.

Proper housekeeping and prudent formulation management can save a plant up to 10% of its use of CFCs. Some recommendations:

- Use closed loop unloading systems,
- Do not flush with CFCs,
- Avoid the use of CFCs for viscosity adjustments,
- Minimize the TDI index.

Recycling/recovery is practiced in several plants in Europe on industrial scale. The ABA is first adsorbed to activated charcoal, and subsequently desorbed through steam or nitrogen regeneration. A precondition is a reduction of the process ventilation, which can lead to exposure problems for production workers. Recovery of curing emissions is hardly feasible, reducing the obtainable overall efficiency to less than 50%. Investment and operational costs are high.

Alternative Auxiliary Blowing Agents

Methylene Chloride (MC)

Methylene chloride's combination of properties, such as a low boiling point, relative inertness, relatively low toxicity and virtually non-flammability have led to its use as an auxiliary blowing agent in the foam industry. Its low photochemical ozone creation potential (PCOP) and lack of ozone depletion potential (ODP) has increased its use dramatically in the recent years, making it a significant CFC-replacement in the manufacture of polyurethane foam. MC's volatility can trigger, however, high concentrations in the production area, requiring careful handling to avoid over exposure. Local and regional health and environmental regulations pertaining to the use of MC vary and may affect the use of this auxiliary blowing agent.

MC is currently the preferred replacement technology in North America, the UK and many developing countries. Recent regulations may limit in the future the allowable MC emissions in the US, which could reduce the application to an interim technology in that country.

MC is capable to replace CFCs without any significant limitations, at lower costs. The "learning curve", however, can be considerable as the process is less forgiving. Also, contamination of MC with iron can cause severe scorching. It is recommended to use only "Urethane Grade" MC. Because of its higher heat capacity it is less successfully used in moulded PUR.

Methylchloroform (MCF)

MCF can be used in situations where the use of MC is restricted. However, MCF is classified as an ozone depleting substance (ODS), and subject to the same phase-out date as CFCs. It is therefore at most an interim solution. Costs are higher than MC, and processing is more difficult, related to the higher heat capacity of MCF.

MCF for flex foam blowing is not permitted in specific regions such as Europe and Canada.

HCFCs

HCFC-141b is technically viable alternative for flexible foam, but is an ozone depleting substance, and therefore at best an interim solution. HCFC-123 is not commercially available as a blowing agent for foams. Several countries have ruled out the use of HCFCs in flexible PUR as it is believed that sufficient other "environmentally more acceptable" options are available.

Acetone

Acetone has been proven fully capable in replacing CFC-11. Precautions must be taken in view of its flammability. Only about 60% is needed compared to CFC-11. Capital outlays and license fees may put the costs close or equal to those of MC.

AB Technology

This technology utilizes the reaction between TDI and formic acid to create an ABA, consisting of equal amounts of CO and CO₂. As this reaction is exothermic, a complete replacement of CFCs is not feasible. Substantial equipment adjustments are needed and monitoring of CO is highly recommended. This technology is used in a few European plants, but has found no acceptance elsewhere, due to safety concerns and limited applicability.

Pentane

At least one company in the US is reported to use pentane as an ABA. The flammability of pentane requires extensive safety precautions similar to the use of hydrocarbons in extruded polystyrene/polyethylene and acetone in flexible PUF. Only about 70% is needed compared with CFC-11.

CarDio Process

The introduction of additional carbon dioxide gas in the foam system during or prior to the mixing of the chemical compounds has been subject of investigation for quite some time. One equipment manufacturer has recently (fall 1993) introduced the so called "CarDio" Technology. In this process ABAs are replaced by physically introduced CO₂. The use of CO₂ poses several challenges to the system:

- The introduction of sufficient CO₂ in the system to allow even the lowest densities;
- Control of the frothing that will occur upon exit of the reaction mixture from the mixing head. This is related to the rapid expansion of CO₂, which has a very low boiling point, under non pressurized conditions;

- How to combine the modifications needed to accommodate the frothing with the manufacture of foam types that need no ABAs and consequently do not froth.

Designers of the CarDio system claim to have these challenges mastered. Currently six industrial production facilities have been completed (November 1994). And four additional units are planned for 1995. At this moment, the technology has to be labelled as "in the process to be industrialized". Its attraction as being cost-effective (CO_2 is low priced and less is needed) and environmentally acceptable (obtained from natural sources, no ODP, low GWP) has captured the interest of the foam producing community.

Chemical Modifications

Chemical modifications have been so far successfully applied in foam softening, but fell short in density reduction.

Extended Range Polyols

These polyols are able to provide a larger range of foam hardness, and, in that way, able to partially replace CFC-11 as a softening agent. Some extended range polyols also allow the use of lower TDI indexes, and will therefore lower the exotherm. This allows in addition a reduction of the foam density. However, a complete replacement of CFC-11, while maintaining the full production range is not (yet) possible. Additional metering systems and tanks are needed, and the price of an extended range polyol is higher than conventional polyol. Extended range polyols are often used in conjunction with special additives (see next paragraph). Extended range high resilience (HR) polyols are particularly successfully applied in moulded applications.

Softening Additives

Several additives have been developed to modify the chemistry of the flexible PUF production process. These additives are currently predominantly softening technologies, and do not allow densities under 21 kg/m^3 . Some additives can be used in addition with extended range polyols and reduced TDI index. In this way, the higher hardness range from the polyol, the integral building properties of the additive and the reduction of the exotherm from the index reduction provide together a system that may be able in the near future to provide the full range of density and hardness while maintaining acceptable physical properties.

Water Blown "MDI" Technology

Water blown MDI technology is widespread in the manufacture of moulded flexible foam because of MDI's properties of inherent softness and lower exotherm, which allows higher water formulations.

Also, several chemical suppliers offer MDI-based flexible PUR systems for slabstock. Some interesting environmental features are:

- no need for auxiliary blowing agents to achieve softness,
- significant lower isocyanate emissions,
- rapid curing,
- lower exotherm, allowing higher water formulations.

This technology is not yet capable of producing very low densities without sacrifices to physical performance, and is therefore limited in its application.

Alternative Manufacturing Technologies

Several technologies have recently surfaced, that could be classified as "mechanical" replacement technologies for the use of CFCs in flexible PUR, predominantly slabstock. Many of the common replacement technologies are:

- environmentally challenged (methylene chloride, methyl chloroform, acetone, pentane, HCFCs), or
- not capable to a full replacement (extended range polyols, additives).

Also, regulations in many countries have intensified the focus on emissions from auxiliary blowing agents, and the need to control these. This, in turn, brings up the problem of the fugitive emissions. Fugitive emissions are 45% to 70% of the total emissions from the manufacture of flexible PUF. Capture and treatment of these emissions in a traditional plant setting seems technically challenging, and most likely cost prohibitive. Traditional technologies, such as:

- incineration,
- liquid adsorption, or
- carbon adsorption

are ill suited for the treatment of low concentration, high volume areas like the storage and curing rooms, from which these emissions typically originate.

The "mechanical" technologies allow the integration of the curing area in the emission control, or allow even to eliminate the use of auxiliary blowing agents altogether.

E-MAX

The E-Max process combines the production and curing steps by encapsulating the developing bunstock in a mold as the foaming mixture is introduced to the foam line. The foam mold allows all emissions from the process to be captured and collected, utilizing only relatively low air flows. There is currently one full scale production

facility in the US. On pilot scale, 85% recovery of ABA has been reported. On industrial scale, recovery of MC in the same range (80-90%) and reduction of TDI emissions to non-measurable levels are reported. The costs are, however, high; retrofitting is not possible and the enclosure of the lay-down and expansion process complicates process control. The fact that no more facilities are constructed indicates the process is not economically attractive.

Accelerated Cooling Systems

The heat generated from the reaction between water and TDI limits the use of chemically generated CO₂ as sole blowing agent. Accelerated dissipation of this energy would allow to increase the amount of CO₂ that can be chemically generated up to a level that would even allow complete elimination of the use of an auxiliary blowing agent for the purpose of density reduction.

Accelerated cooling in itself is not patentable and several companies operate some kind of in house design of this technology. UNDP and The World Bank offer a design including a full set of drawings for box-foam producers ("UniCure"), that can be manufactured locally as part of a project covered by the MLF. Projects for about 90 of such units are in the mean time approved through collective projects in Indonesia, Malaysia and The Philippines, and expected to be installed in early 1995.

There are also several proprietary systems on the market that apply this technology in several variations, sometimes including treatment of process emissions, such as:

ENVIRO-CURE

The Enviro-Cure process is designed to eliminate the need of an auxiliary blowing agent for cooling purposes and, for that matter, for density reduction. The remaining function of an auxiliary blowing agent--softening of the foam--can relatively easily be substituted by chemical softening techniques. Enviro-Cure achieves this through an enclosed conditioning area, designed to rapidly cool foam blocks through a closed loop air stream. Emissions are in this way re-introduced in the foam that functions as an emission filter. The process is very suitable to the Vertifoam process (because of its inherently thin skins). One unit has been recently installed at a Varimax plant. One unit is currently under construction in China financed by the MLF. The process is patented, and subject to a license fee.

The economic consequences of the utilization of this process depend on local conditions. In regions where proposed regulations may well forbid the use of auxiliary blowing agents altogether, significant potential savings can be obtained compared to the alternative of raising the density. Compared to the use of MC, the process will generate higher chemical costs, in addition to capital and operating costs, but provides space savings related to the elimination of the need for a curing area.

The feedback from future licensees will be needed to allow for a complete evaluation of the merits of this process.

RAPID CURE Process

Similar to the Enviro-Cure process, the "Rapid Cooling" process is designed to completely eliminate the need of auxiliary blowing agents, without sacrificing quality or product range. To achieve this, a two stage cooling device is directly attached to the foam production tunnel, replacing the conventional curing/cooling area. Significant reformulation is required to implement softening techniques and to make up for reduced crosslinking, related to the elimination of unreacted TDI in the initial phase of the cooling. The "Rapid Cure" process is patented, and requires license fees. The chemical costs are reported to be very close to those of methylene chloride blown foams. Capital cost are highly dependant on local lay-outs.

The process is so far applied in one facility in the US. Another unit is recently ordered as part of an MLF sponsored project in Egypt.

Variable Pressure Systems

It is well known that the blowing efficiency increases with decreased atmospheric pressure. This allows at higher altitudes the manufacture of lower density foams with less, or no, auxiliary blowing agents through a higher effectiveness of the water/TDI generated CO₂. This principle can be applied at lower altitudes by encapsulation of the foam production line and subsequent reduction of the process pressure. Conversely, the increase of pressure reduces the effectiveness of the water/TDI induced gas generation and in this way allows the generation of higher urea levels (a by product of this reaction). Currently two companies offer non-ODS technology based on variable pressure:

The "VPF" Technology targets continuous foam production lines. Two production units, utilizing this principle, have been in operation for over a year, with good results. At least one other installation is under construction. The technology is patented and marketed through a licensing system. The capital equipment requirements for VPF are high - approx 3 to 5 million \$US.

The "CEF" (Controlled Environment Foaming) Technology targets the "Box" Foam market following essentially the same technology, but is drastically in reduced complexity. The technology has just been recently presented publicly and commercial installations are not yet in production.

Product Substitutes

There are no indications that the elimination of CFCs in flexible PUR has caused any substitution of this material in its main applications (comfort in automotive, bedding and furniture) where it has achieved high and ever increasing market penetration. Flexible PUR has

other properties that are under scrutiny such as its flammability. This is a perceived threat to its viability in certain high risk applications and a more realistic potential reason for substitution than relative small or non-existing price increases related to the replacement of CFCs.

Substitution rates could be different in technical applications such as acoustics, filtering, gasketing, packaging etc, where flexible PUF had a much lower degree of penetration. However, in this area ABAs never played a very significant role in the production process and CFC replacement will therefore be a minor issue. Conversely, the development of variable pressure foams may make flexible PUF more competitive in packaging foams through the possible introduction of a higher polyurea content.

The largest not-in-kind product substitute for flexible PUR is polyester fibre-fill. It is currently used as an outer "wrap" over flexible PUR to give soft initial feeling. Complete substitution of polyester fibre for flexible PUR can successfully be used in low-stress applications such as furniture backs or outside facings, however, it has limited use in high-stress applications such as seats because of its high compression set properties.

Conclusions

- CFC-11 has been or will be eliminated from flexible slab and moulded foam by January 1, 1995 in all of the major developed countries;
- The main technical alternative at this time is methylene chloride, however, its future is uncertain because of tightening emission requirements;
- Emerging emission regulations will put significant pressure on the future use of auxiliary blowing agents entirely in question, with the notable exception of injected CO₂;
- Without ABAs, the flexible foam industry would mainly use various chemical and process options;
- At this time, there is no clear "best-choice" and several options may be used;
- There remains ongoing developments and other alternatives may emerge; and
- Large scale product substitution for flexible polyurethane foam is unlikely.

INTEGRAL SKIN AND MISCELLANEOUS FOAMS

Products and Applications

This section includes the many types of polyurethane foams which do not fall into the rigid or flexible category. The list of applications is long and varied.

Integral skin and miscellaneous polyurethane foams include:

Integral Skin

- flexible (or semi-rigid) integral skin foams for steering wheels, headrests, armrests, shoe soles, beer barrels, etc;
- rigid integral skin foams for computer cabinets, skis, and tennis rackets;

RIM

- microcellular high-density foam for exterior body parts of automobiles;

Non-Insulation Rigid

- low-density packaging foam;
- floatation foam;
- floral foams; and,
- energy absorbing foams for side impact in automobiles.

The principal benefits of polyurethane use for these applications are performance, ease of processing, and cost. CFCs have essentially been eliminated in these foams in most developed countries.

Production Process

Integral skin foams are molded foams, manufactured either by injection into closed vented molds (i.e. steering wheels) or by pouring into open molds (i.e. skin soles). These foams are characterized by a high density outer skin and a low density, softer core. The density gradation results from (a) blowing agent condensation at the mold surface compacting the cells of the urethane foam, and (b) overpacking of the mold.

Microcellular high density foams (RIM) are manufactured via injection into closed molds, in many cases using large presses to maintain clamping pressure and produce parts within dimensional tolerances. The microcells form air nucleation and also from small amounts of CO₂ (resulting in most cases from residual water).

Non insulation critical rigid foams are manufactured via a variety of processes including spray, molding or rigid slabstock, using conventional or high pressure urethane dispensing equipment.

Most integral skin and miscellaneous foams are open cell, where the blowing agents used in manufacture are emitted to the atmosphere during the foaming reaction or soon thereafter. Rigid integral skin and flotation foams are closed cell, but low thermal conductivity is unnecessary in these products.

Global Consumption of CFCs and HCFCs in Integral Skin and Miscellaneous Foams

According to global estimates, 2000 tonnes of CFCs were used in integral skin and miscellaneous polyurethane foam manufacturing in 1993. This estimate represents less than 1 % of CFCs used in all foam production. In 1990, global estimates placed CFC use at between 7,400 and 9,900 tonnes in these applications.

According to global estimates, 300 tonnes of HCFCs were used in integral skin and miscellaneous polyurethane foam manufacturing in 1993. This estimate represents 0.5 % of HCFCs used in all foam production.

Technical Options to Reduce CFCs in Integral Skin and Miscellaneous Foams

Current

Integral Skin

For flexible (semi-rigid) integral skin foam applications deemed automotive safety related (e.g. steering wheels), most polyurethane systems currently utilize HCFC-22, or to a lesser extent HCFC-141b, as the blowing agent. This results in a well defined skin, with good overall physical properties. The skin is relatively thick and its surface is smooth and paintable. Some conversion to all water blown systems has occurred in North America and Asia. Some moulders in Europe and Canada are producing integral skin foams for armrests using pentane as blowing agent to form the skin.

In North America and Asia, all flexible (semi-rigid) integral skin foams, other than for automotive safety applications and been converted to zero ODP blowing technology (no CFCs or HCFCs). Most applications have been converted to all H₂O or HFC-134a blowing technology. In Europe, the situation is similar, although HCFC-22 is still being used but is expected to be phased out shortly.

Rigid integral foams have essentially all been converted to water blown systems, although some HCFC-141b is still being used in Asia.

Non-Insulation Rigid Foams

All open cell rigid foams (e.g. packaging, floral and energy absorbing foams) have been converted to CO₂ (water blown) technology (zero ODP).

Closed cell rigid foams used for flotation currently utilize mostly systems with HCFC-22/H₂O blowing technology. However, this business is converting to proven zero ODP technology -- HFC-134a for pressurized dispensing systems and H₂O/CO₂ for conventional systems.

Long Term

For flexible integral skin foams used in automotive safety related equipment, development efforts are continuing down several pathways including HFC-134a, all H₂O, molecular sieve and pentane. The molecular sieve technology has been introduced in Europe and involves H₂O trapped in a microporous structure being released via heat of reaction during the foaming process. With the isocyanate no longer available for reaction, the H₂O vapor condenses at the mold surface forming a thin skin.

All H₂O blown systems are anticipated to be the future for manufacturing the non-automotive safety related integral skin foams. Development efforts are being concentrated on improving foam physical properties (such as abrasion resistance for all H₂O blown shoe soles foams using polyether polyols).

Product Substitution

In a few applications, where a very pronounced skin is deemed necessary, an alternative is to use H₂O blown flexible foam behind poly vinyl chloride (PVC). This approach is being used presently in some applications such as arm rests for furniture and tractor seats.

Conclusions

For the most part, technology is in place to enable manufacture of integral skin and miscellaneous foams using zero ODP technology. The remaining area still needing development is flexible integral skin for automotive safety. In this case, some conversion to zero ODP (HFC-134a and all water blown) has already taken place. Several alternative technical options have been identified and are being pursued in product development to enable full conversion to zero ODP.

Chapter Four

PHENOLIC FOAMS

Products and Applications

Phenolic foams still represent well under 5 % of the foamed insulants used world-wide. However, their excellent generic fire properties (particularly their extremely low smoke emissions) are establishing the products in many applications previously served by other insulation products. Evidence of this fact is revealed by the growth in their use since 1986 despite strong recessionary factors in some regions over recent years. With increasing concern over fire safety world-wide, this growth is anticipated to continue making the inclusion of phenolic foams in this report a necessary step despite their relatively low current base.

The prime cause of growth has been the availability of processes to produce closed-cell products to compete with other foam equivalents. The requirement for high thermal efficiency naturally drove the phenolic foam industry towards CFCs during the early to mid 1980s and several such technologies were developed around that time.

Phenolic foam products have gained acceptance in many types of public and commercial building. There is a small but significant level of substitution against fibrous products where cleanliness and moisture resistance can be offered without unnecessary loss of fire performance. This is typical in the building services sector (Heating & Ventilation), where insulation is often exposed. Pipe laggings are an example.

However, by far the greatest proportion of substitution which has occurred against other foam products is in the flexibly faced laminate sector--albeit that market acceptance is varying considerably by region. This latter fact has caused some North American producers to reconsider their positions in recent times. In Europe, such laminates are widely used for wall and roofing applications, particularly within the growing single-ply roofing market and, not surprisingly, designers and builders are seeking the most fire-safe products for this purpose. Cost usually rules against phenolic foams when considered for the domestic environment.

More recently, activity has increased in the use of phenolic foams in rigid faced panelling for doors and partitions. Closed-cell foam technology has been equally applicable for these applications.

There is still some residual usage of open-celled phenolic foam for specific market requirements. A prime example of this is its use for floral arrangements. The unique wetting properties of this particular product make it virtually irreplaceable. However, these properties are not reliant on the use of CFCs and most production had already switched to hydrocarbons on the basis of cost.

More orthodox open-celled phenolic foams are still used in some countries, most notably the former Soviet Union, as prime insulation. As these foams exhibit poorer insulation characteristics than those made from the more recently developed closed-cell technologies outlined above, there has been pressure to transfer these technologies under licence or other co-operative agreement.

Production Processes

Discontinuous Processes

Several discontinuous processes have been developed for closed-cell foams, but undoubtedly the most prevalent is the Block or Bun process. This has been particularly dominant in Europe where the process lends itself to the varied requirements of Building Services market. Complex computer-controlled cutting equipment optimises yields from blocks when cutting pipe sections. Despite this, yields can be as low as 50% for the more awkward shapes.

Other discontinuous processes include the manufacture of rigid faced panels by injection (normally referred to as "pour-in-place"). Multi-daylight and oyster-press routes have been followed, but investment in these more recent sectors has only re-emerged following the development of thermally efficient CFC-free technology.

Most, if not all, discontinuous processes have used CFC-11 and/or CFC-113 to obtain their high thermal efficiencies historically. Accordingly, most plant technologies, and their associated installed units, are unable to handle low boiling blowing agents. Additionally, few plants are flame-proofed. These factors have inhibited the move to alternative blowing agents, particularly the low boiling HCFCs and HFCs. Furthermore, it has to be said that appropriate plant and process technologies for this purpose are likely to be difficult to achieve and, therefore, still seem some way off.

Continuous Processes

Within the range of continuous processes, lamination with flexible facings has been the major development over the last five years. There has been less focus on rigid faced lamination and continuous block to date, although these may follow as and when CFC-free technologies become available. The machines used for continuous lamination are, in the main, more capable of processing low boiling blowing agents and, accordingly, CFC-114 has been a common constituent within several technologies historically. It should be stressed that it is

the process rather than the machinery per se which facilitates the use of these materials. Therefore, it is unlikely that much of the associated technology will be transferable to the discontinuous operations.

Global Consumption of CFCs in Phenolic Foams

The progress in reduction of CFC consumption within the phenolic foam sector has been steady since the last review in 1991. As will be seen in Section 4.5, technologies now exist to replace CFCs in virtually every application. However, progress on phase-out has been hampered in some regions by the continuing availability of CFCs at low price. Without fiscal instruments or end-use controls in-place, some markets have continued to opt for the lowest cost/lowest risk option. As availability of CFCs declines over the next 12-18 months it is anticipated that there will be a rapid further reduction in use in those regions where it has not already occurred:

Table 4.1 Estimated Global CFC Consumption for Phenolic Foams (Tonnes)

Region	1986	1990	1993
North America	700	1,500	
Western Europe	400	700	
Japan	300	400	
Former USSR / Eastern Europe	0	NIL	
Rest of World	0	100	
Total	1,400	2,700	628

Global Consumption of HCFCs in Phenolic Foams

In most cases where phenolic foams are being used as insulation, HCFCs have been the preferred substitute. Accordingly, the growth in HCFC use shown in table 4.2 below reflects, to a degree, the reduction in CFCs also achieved. The potential use of hydrocarbons may influence this pattern in due course, but for the reasons given in Section 4.5 this is not imminent. Similarly, the introduction of HFCs could have an impact on HCFC use towards the end of the century.

On this basis, consumption of HCFCs is expected to grow to a level of at least 2,500 tonnes by 1998 and this may be increased further if phenolic foam continues to make market share gains at the expense of other insulants.

Table 4.2 Estimated Global HCFC Consumption for Phenolic Foams (Tonnes)

Region	1986	1990	1993
North America	0	75	
Western Europe	0	50	
Japan	0	10	
Former USSR / Eastern Europe	0	0	
Rest of World	0	0	
Total	0	130	610

Technical Options to Reduce Ozone Depleting Compounds in Phenolic Foams

The phenolic foam industry worldwide continues to be extremely active in seeking alternative blowing agents for its products. As mentioned in the 1991 report, spending in excess of five million US dollars (estimated to be 5 per cent of annual turnover) has been undertaken in seeking solutions. The industry has undoubtedly benefitted from having technology development teams already in place as a consequence of the relatively recent emergence of the "base" technologies.

Current

Hydrocarbons (open-celled foams)

Achieving high thermal efficiencies is important to the growth of phenolic foam use worldwide. In this context, open-cell pentane blown foams have not impacted the market substantially, being 60 percent less efficient than their CFC-containing counter-parts. In most cases, they have been superseded by HCFC-blown foams except where zero-ODP options are essential.

Hydrocarbons (closed cell foams)

2-chloropropane continues to be of interest in certain quarters and the commercial adoption of this technology for phenolic foam is understood to have been achieved by at least one company in Europe. However, the material's finite ODP would appear to rule it out as a long term solution.

HCFCs

The emergence of HCFC-141b as a readily available alternative has substantially influenced the phase-out rate of CFC use in the industry. Most processes worldwide have been able to accommodate the blowing agent, albeit with the use of additional cell-modifiers in many cases.

Previous TOC reports have referred to the limitation of discontinuous processes with respect to the blowing agent boiling points they can accommodate. For this reason, HCFC-141b has been the only viable alternative despite its slightly higher ODP.

Continuous processes, on the other hand, are more versatile in this regard and can use blowing agents such as HCFC-142b and HCFC-22. However, it has been found that the emission levels experienced on many of these processes using such low-boiling HCFCs are significant enough to have greater impact on the environment than the use of higher-boiling alternative.

At first sight this would appear to be the outcome of poor process engineering. However, the reality is that the emulsion-based technology, on which all phenolic foams rely, often requires highly sophisticated techniques for distribution of material on to the process conveyor. These techniques can cause blowing agent losses well in excess of those normally anticipated with solution-based technology.

Longer Term

Hydrocarbons (closed-cell foams)

Further progress has been made with closed-cell foam technologies using hydrocarbons since the last Technical Options Review in 1991. At least two discontinuous technologies now exist and it is likely that similar chemical solutions could be transferred to continuous processes if other factors allowed.

The major problem with the commercialisation of these technologies has been the characterisation of end-product fire performance. As the distinctive value of phenolic foams to the insulation industry lies in their inherent fire and smoke properties, such uncertainty about fire performance is a debilitating problem.

Work with the UK Government has been initiated to establish comparisons with more traditional CFC-blown systems but the magnitude of this task should not be underestimated in view of the variety of end-products and applications to be considered.

In view of these uncertainties, it has proved difficult to verify technologies on continuous processes, since significant plant investment is required to handle hydrocarbons safely in most installations.

HFCs

The two factors working against the use of HFCs in phenolic foams historically have been:

- (i) The impact of the price of HFCs on the cost base of foams (the

sensitivity is high), and

- (ii) The lack of ambient boiling HFCs for discontinuous processes.

Since the 1991 Review, HFC manufacturers have been addressing the needs of the foam blowing industry in a more focused way. Several HFCs have emerged with potential of being used in both continuous and discontinuous processes. These include isomers of HFCs 245, 356 & 365. However, full toxicological testing will be required on these before they can be introduced commercially and progress is therefore likely to be hampered until 1998 or 1999.

Pricing issues will also remain a key factor in the final acceptance of such solutions.

Recovery/Recycle/Destruction

Closed-cell phenolic foams undergo similar emission processes to other closed-cell, CFC-blown rigid foam boardstock: small amounts of CFCs are emitted during the production process, while the remaining CFCs, stored in the foam cells, are released very slowly over the life of the foam, owing to extremely low gas permeability.

Theoretically, emissions during manufacture could be collected by carbon adsorption techniques, but in practice the actual process efficiencies would be extremely low. In contrast, the significant cutting losses associated with some discontinuous processes have offered an ideal opportunity for recovery and recycling. However, despite considerable efforts, the efficiency of recovery by carbon adsorption has not exceeded 50%.

In spite of this, the technology may continue to have benefits for the recovery of HCFCs and HFCs in future.

The use of material recovered from other processes has also been investigated and, for the most part, this has proved successful. With respect to destruction processes, incineration techniques are being investigated in Europe under the European Union's Demolition Waste Directive. Whilst phenolic foam has not been specifically characterised as yet, this method of destruction could prove an effective source of energy recovery.

Product Substitutes

Phenolic foams are noted for their excellent thermal efficiencies and outstanding fire performance. These factors, together with their cleanliness, moisture resistance, space-saving and integrity must all be taken into account when considering product substitution. In view of this wide range of product benefits, it is difficult to generalise about alternatives. If they exist at all, they are likely to be very market specific. Little actual substitution has taken place to date.

Conclusions

From a technical viewpoint, the phenolic foam industry is now in a position to phase-out of CFCs. In this regard, the industry has undoubtedly benefited from having technology development teams already in place as a consequence of the relatively recent emergence of the "base" technologies.

The prime replacement blowing agent to date has been HCFC-141b although some low-boiling blowing agents (HCFCs-142b and -22) have also been used in continuous processes.

Although hydrocarbon-based technologies exist there is some concern about their early introduction. This arises from the potential impact on end-product fire performance which is, as yet, unquantified.

In practice, the phase-out of CFC use has been limited by commercial and liability considerations which have arisen in the recessionary market environment worldwide. This trend has been exacerbated in Europe by the availability of CFCs on a wider basis and at lower prices than had originally been anticipated. Notwithstanding this, the rapid reduction in allowable CFCs in Europe and North America through 1994/95 will drive change effectively.

In the longer term, HFCs offer the potential of replacing HCFCs as the major blowing agents for the industry but clearly the issue of global warming needs to be dealt with intelligently to avoid losing the opportunity of improving energy efficiency and reducing carbon dioxide emissions by this route.

Chapter Five

EXTRUDED POLYSTYRENE

EXTRUDED POLYSTYRENE SHEET

Products and Applications

Extruded polystyrene foam sheet is a thermoformable material used primarily to manufacture food service and food packaging products, such as hinged carry-out containers, single-service plates, cups, egg cartons and food trays. Other applications include dunnage, laminated sheets, and wrap-around labels.

Food Service and Packaging

Food service applications for extruded polystyrene foam sheet include the manufacture of cups, plates, bowls, and hinged-lid containers, while food packaging applications include the production of meat trays, egg cartons, and produce trays. In 1986, food service and packaging applications consumed about 83% of the CFCs used for rigid polystyrene foam packaging.

CFCs were attractive blowing agents for some foam food service products because they contributed to the products' ability to insulate food and beverages at the proper temperature and to provide appropriate moisture resistance. In food packaging, CFCs also contributed to the products' moisture resistance; therefore, the end products eliminate the need for frequent in-store rew wrapping.

Dunnage

Dunnage is loose fill packaging materials such as foam "peanuts," pellets, and chips. This foam is used to protect products during transit and, thus, reduce the amount of breakage. Foam dunnage is reusable, sanitary, lightweight, and moisture resistant.

Laminated Foam Sheets

Laminated foam sheets are used as art board and in insulated packages. Providing aesthetic versatility when used art board, laminated foam sheet is rigid yet lightweight, and readily

accepts printing inks. In insulated packaging applications, laminated foam sheets are lightweight, rigid and moisture resistant, in addition to providing thermal insulation.

Production Process

Extruded polystyrene foam sheet is produced by a process that mixes polystyrene resin with additives and melts the mixture to a low viscosity in a two-stage screw extruder. During the process, blowing agents are injected into the extruder under high pressure and dispersed into the polymer melt.

Then, this mixture is cooled and forced through a die under controlled pressure. As the molten polymer exits the die, the dissolved blowing agent vaporises and expands. This reaction causes the plastic to foam. An annular die is used to form a tube, which is subsequently slit to make foam sheets.

Final production stages involve cooling, shaping, cutting or winding the foam into the desired form. Extruded foam sheet is normally aged two to four days prior to thermoforming into the desired form. Approximately 80% of the extruded polystyrene foam sheet produced consists of foam sheet that is thermoformed into a variety of products.

The thermoforming step typically generates a substantial amount of foam scrap. In some cases, 30% to 40% of the extruder feed becomes scrap. Manufacturing processes commonly include grinding and repelletising steps after final cutting and thermoforming.

The pelletised foam scrap recovered from thermoforming is recycled back to the extruder feed. The typical extruder feed mixture is 65% virgin polystyrene and 35% recycled polystyrene.

Global Consumption of CFCs in Extruded Polystyrene Sheet

In Western Europe, North America, Japan and Australia the food service products and meat/poultry trays are no longer produced with CFCs or HCFCs except for one or two isolated manufacturers.

Most of the packaging manufacturers have converted their production to hydrocarbon blowing agents, particularly pentane and butane combinations with smaller amounts of HCFC-22, HFC-152a and CO₂.

Alternative blowing agents to CFCs such as HCFC-141b, HFC-134a and HFC-152a have been evaluated and sometimes even used in production. Although these products offer advantages in environmental performance, disadvantages such as reduced processability, lack of generally accepted approvals for food contact and price made most of the industry decide to go to hydrocarbons.

The converters of laminated foam sheet have also changed over to hydrocarbons.

Without exception it is fair to say that hydrocarbons are the standard of the industry today and that halogenated products as blowing agents for the production of polystyrene foam sheet have been phased out, at least in the developed world.

In 1993 it is estimated that the global consumption of CFC's in the extruded polystyrene sheet industry was of the order of 12,200 tonnes. Of this some 87% was estimated to have taken place in countries operating under Article 5.1. The *1991 UNEP Foams Technical Options Report* mistakenly stated that the CFC phase-out was taking place globally. The 1994 report, however, has uncovered a significant use of CFCs in this application in developing countries. Taking the 1986 base of around 20,000 tonnes the 1993 figure nevertheless represents a reduction of around 40%.

The alternative technologies of hydrocarbon and CO₂ are readily available and transferable.

Several developing countries have indicated that they plan conversion out of CFC's in 1995. There are proven technologies available to replace CFCs and, provided capital can be secured, could occur much faster than the 10 year grace period allowed under the Protocol.

Estimates for global consumption of HCFC's are just over 280 ODP-tonnes for 1993, the bulk of which took place in North America.

Technical Options for Blowing Agents in Extruded Polystyrene Foam Sheet

To be an effective blowing agent for extruded polystyrene sheet used for packaging, substances must satisfy certain technical criteria:

- solubility - there must be adequate solubility in the molten resin and low solubility in the extruded foam products;
- safety - substitutes must be low in toxicity and their flammability characteristics must also be considered;
- stability - high thermal and chemical stability is required in the manufacturing process;
- diffusivity - low diffusivity is necessary for post-expansion; and
- environmental acceptability

The solubility of the blowing agent in the molten polymer is a critical property. If the blowing agent separates from the polymer matrix, gas pockets will form.

Stringent requirements for food packaging also pose challenges as manufacturers seek new blowing agents. In many countries, the use of any substance used to manufacture a product for food applications requires regulatory clearance.

Current Options

Hydrocarbons

Hydrocarbons are the blowing agent used today sometimes in combination with CO₂ for cost reduction reasons.

Hydrocarbons are also an immediately available option. N-pentane, butane, isopentane and isobutane are readily available petroleum products. Several manufacturers are already using hydrocarbons alone or in combination with carbon dioxide or HCFC-22.

On a cost per unit weight basis, pentane and butane are the cheapest available blowing agents for foam sheet food service and packaging applications. They offer excellent solubility properties, better plasticising properties, and the required diffusivity.

Polystyrene foam packaging products made with hydrocarbons offer a similar high quality as those made with CFCs. Many companies in Europe and the Far East currently use hydrocarbons or are converting from CFCs to hydrocarbons. The primary concerns associated with the use of hydrocarbons are VOC emissions and flammability.

Regarding emissions, hydrocarbons are photochemically reactive volatile organic compounds (VOCs) that contribute to ground level ozone pollution. Emissions may be reduced through the use of recovery and reuse technology, incinerators, or catalytic converters. In addition, manufacturers using hydrocarbons must obtain permits for their facilities and meet allowable local emission limits. In some countries, such as the United States, obtaining permits for facilities can be difficult or even impossible in high pollution areas and thus, the hydrocarbon solution can be of real concern.

Consequently, in areas where hydrocarbon emissions are restricted, additional investments could be as high as US\$1 million to install equipment to comply with air pollution regulations and worker safety. Either destruction of the blowing agents via incineration or recovery of the blowing agents via carbon adsorption is required.

Modifications required to ensure worker safety include anti-static guards, spark arresters, and ventilation equipment to diffuse heavy hydrocarbon vapours, as well as employee retraining. Actual conversion costs will vary depending upon plant size, plant locations and emission control requirements.

Operating costs for using hydrocarbons, however, are lower than those for CFCs. In fact, it is estimated that manufacturers can expect a payback around 18 months on the capital investment necessary to meet flammability and emissions criteria.

HCFC-22

In many cases HCFC-22 has been used for a short while, since it offered an improved environmental performance versus CFC-12 and CFC-11 and allowed rapid conversion without major plant modifications. HCFC-22 has been used as an interim solution in the search for alternative blowing agents until more suitable options are developed and implemented.

HFC-134a and HFC-152a

Both products have had attention as possible replacements for CFC-12 in polystyrene foam sheet applications.

HFC-134a has been investigated as a possible replacement blowing agent. Its inflammability and its VOC exempt status in the US are considered advantageous. No regulatory approval for food contact, difficult processing and high cost are the reasons for lack of commercial use.

The use of HFC-152a in this application is limited to the US. It has better processing characteristics than HFC-134a and carbon dioxide but not as good as hydrocarbons. Its flammability characteristics are similar to those of hydrocarbons but in the US it is VOC exempt which has led to its use as an alternative to hydrocarbons where recovery and incineration would have had to be installed. It is sometimes used in combination with other zero-ODP options.

Long Term Options

The direction the foam industry will take in the long term regarding blowing agents is towards atmospheric gases such as CO₂, nitrogen and water. The time frame of implementation is uncertain since significant hurdles in processing need to be overcome and acceptance by market is necessary because of differences in the physical appearance of the trays.

Today technology using 100% CO₂ as a blowing agent has been implemented by a few pioneers in the market. In the US two converters are fully commercial in food service applications with 100% CO₂. In Brazil the whole product range has converted to 100% CO₂. In Europe two manufacturers are in the process of converting their production to 100% CO₂.

With 100% CO₂ the processing window is narrowed compared to CFCs and hydrocarbons. Due to the low molecular weight of CO₂ only small quantities are needed. The balance of

properties of density, aesthetics and processability differ significantly from the blowing agents mentioned above. A cost effective solution can be defined, but is dependent on market acceptance. Some manufacturers have difficulties in producing the full product range with CO₂ alone.

Nitrogen has been evaluated and is used commercially for thin gauge/high density labels. Other applications are not feasible due to the limitations in thickness and density which can be produced.

The long term developments are those which facilitate the use of atmospheric gases as blowing agents. Hardware developments such as die and screw designs are taking place. Also new or improved technologies are being evaluated. On the other hand polystyrene resin or additive developments may allow the use of atmospheric gases. These kinds of developments may take several years before break through and commercialisation is achieved.

Conclusions

Since 1986 manufacturers of extruded polystyrene foam sheet in the packaging market have moved away from fully halogenated CFCs. Today's market standard for blowing agents are hydrocarbons (although alternatives such as HCFC-22, HFC-152a and CO₂ are currently being used but to a much lesser extent). Except for one or two converters every manufacturer has converted to hydrocarbons in Europe often at high investment cost.

The ultimate direction for the foam industry with regards to blowing agents will be atmospheric gases, which will require a significant effort from the whole industry. Globally there are now 6 manufacturers out of about one hundred using 100% CO₂ as blowing agent.

There are no technical obstacles to phasing out CFCs faster than the 10 year grace period allowed in Article 5 countries because zero-ODP technology based on hydrocarbons and CO₂ is readily available and transferable from the developed world.

EXTRUDED POLYSTYRENE INSULATION BOARD

Products and Applications

Polystyrene foam boardstock was invented in Sweden in the early 1940s but was further developed to the extrusion process in the United States. It is a rigid foam with a fine closed-cell structure. The original blowing agent was methyl chloride, not CFCs. Extruded polystyrene foam insulation made with CFC-12 was introduced to the market in the early 1960s.

Globally, approximately 90% of extruded polystyrene rigid foam boards are used for thermal insulation purposes. The cellular products consist almost entirely of polymer and blowing agent. The type of blowing agent used determines the character of the cellular structure formed during the manufacturing process. There are two main types of foam boards available:

- boards with a smooth skin covering the two principal heat transfer surfaces,
- the main application of the self-skinned material includes insulation for roofs, floors, and walls in dwellings, commercial and agricultural buildings. In some northern countries, another major application is the protection of roads, airport runways and railways against frost-heave by laying the insulation boards in the earth below the pavement and rail permanent way;
- boards with a planed or cut cell surface that provides grip for plaster, adhesive, and pour-in-concrete -- the main application for this product includes wall insulation of concrete buildings, tile and plaster backing, core material for sandwich panel construction, and low temperature space. There are a number of small specialty applications in most geographical markets as well.

High moisture resistance combined with mechanical strength makes extruded polystyrene insulation both an economical and practical material for below-ground building applications, such as basements, foundations and earth-sheltered homes, and inverted roof applications, where the waterproofing membrane is below the insulation material.

Other properties of extruded polystyrene foam include:

- low thermal conductivity;
- resistance to freeze-thaw deterioration;
- excellent compressive strength and dimensional stability (low shrinkage); and
- good handling properties, including low toxicity and low insulating gas diffusion loss with time.

Production Process

The manufacturing of extruded polystyrene foam board for insulation purposes involves an extrusion process similar to that described for sheet. Polystyrene resin is mixed with additives, then continuously fed into an extruder where it is melted. Blowing agent, continuously injected under high pressure, is dispersed in the resin to form a foamable gel. The gel is then cooled and extruded through a rectangular cross section die where the blowing agent volatilises, causing the plastic to assume a foam structure.

After the foam has been formed, it is transported away by a continuous conveyer belt and cut into appropriate lengths and widths. This cutting section can also include equipment to remove the skin (i.e., make planed boards). Internally generated scrap is recycled within the plant. In order to be recycled the scrap has to be reground with consequential release of cell gases.

In closed-cell insulation foams, such as extruded polystyrene, the blowing agent performs two functions:

- it makes the gel foam, and
- it contributes insulation value to the foam.

The blowing agent which stays in the foam to provide insulation value, the primary blowing agent, is sometimes called the insulating gas. A second, or auxiliary, blowing agent is sometimes used to support the foaming process; another proprietary technology uses vacuum foaming. In all processes the primary blowing agent must be present to provide characteristic high level insulation performance.

Extruded polystyrene foam insulation board production units operate in North America, Japan, South Korea, Egypt, Israel, Saudi Arabia, Kuwait and all countries in western Europe except Luxembourg, Ireland, Portugal, Denmark and Switzerland. In eastern Europe at least one plant is operating in Hungary.

It is believed that no production currently exists in other countries of Eastern Europe, Australasia, the former Soviet Union, Central and South America and Central and South Asia.

Global Consumption of CFCs and HCFCs in Extruded Polystyrene Insulation Board

Approximately 17,600 tonnes of CFC-12 were used worldwide in 1986 in the manufacture of extruded polystyrene foam insulation board. At that time, extruded polystyrene insulation boards consumed approximately 7% of all CFCs used in foam applications. In spite of market size increases ranging from 30% to over 80% in the three main producing areas of North America, Japan and Western Europe, CFC-12 consumption had decreased to 12,000 tonnes by 1990.

This trend has accelerated such that by the beginning of 1994 in these three main producing areas the phase out of CFC's was complete; 1993 was thus a year of major conversion effort with 1993 consumption of CFC's was 2,215 ODP-tonnes.

CFC-12 consumption by the world's extruded polystyrene insulation industry has decreased by 87% from 1986 to 1993. Taking the 12,000 tonnes in 1990 as a base the 1993 represents a further reduction of 81% in only 3 years.

This consumption data is a combination of accurate input received on a confidential basis from all producers in North America, Japan and all but two of the producers in the European Union, and industry estimates for other producers.

The 1993 consumption of HCFCs was 1,804 ODP-weighted tonnes. This is approximately 30,100 tonnes of HCFCs.

Thus, consumption of weighted ozone depleting substances by the world's extruded polystyrene insulation industry has decreased by 77% from 1986 to 1993.

Technical Options to Reduce Ozone Depleting Compounds in Extruded Polystyrene Insulation Board

Current Options

Blowing Agent Requirements

A blowing agent is usually a volatile, chemically stable compound, and by its introduction into the molten polymer, it reduces the density of the product by the formation of a myriad of closed cells within its structure.

Until the late 1980s, CFC-12 was the traditionally preferred blowing agent for extruded polystyrene insulation boards because of its attractive properties:

- low toxicity
- non-flammability
- good solubility in polystyrene
- compatible boiling point (-30°C) and vapour pressure for extrusion process
- very low diffusivity through polystyrene
- low thermal conductivity
- chemical inertness; and
- thermal stability at process conditions.

At the time of writing of the first UNEP Foams Technical Options report (June 1989), the worldwide extruded polystyrene boardstock industry established that by the end of 1993 CFC-12 use could, from a purely technical viewpoint, cease completely.

There were two substitute materials identified to successfully replace CFC-12, given sufficient time for thorough product research and development efforts for various applications and manufacturing processes. These replacement candidates were HCFC-142b and HCFC-22.

HCFC-22 and HCFC-142b

The availability of HCFC-22 did not present any problems, but that of HCFC-142b, the key insulating gas and blowing agent, did. HCFC-22, however, has a relatively high permeation rate out of polystyrene and does not provide the long-term insulation value required and is therefore considered a secondary blowing agent. HCFC-142b is clearly the preferred primary blowing agent.

Conversion to HCFC-142b, either alone or in combination with other auxiliary blowing agents including HCFC-22, meant not only considerable investment in manufacturing ancillary equipment, product reformulation, and performance evaluation, but also in cost.

Blowing agents are a significant part of the total cost of the product. There is however no premium price to be obtained for more environmentally benign products in the market.

Approximately 75% to 85% of the HCFC-142b used in the manufacture of extruded polystyrene insulation is retained in the foam after production. The remaining blowing agent is primarily lost via foam forming and shaping processes during production.

HCFC-142b is the blowing agent/insulating gas providing the product with its low overall thermal conductivity.

As the insulating gas, it performs two main functions:

- it promotes the physical processes necessary to make the foam; and
- it provides thermal properties that improve the insulation performance (especially long-term) in the boards.

The blowing agent function is often supplemented by auxiliary blowing agents such as CO₂, methyl chloride (Japan), ethyl chloride (Japan, Canada, USA) and hydrocarbons (butane and pentane). These compounds do not provide long term insulation value and are used solely as blowing agents to achieve low product densities.

The foam insulation manufacturer must make critical blowing agent and process modification choices to provide the best products for particular market applications. Different producers in the same or different markets may make different choices. In fact, not all alternatives may be usable in each process of a particular manufacturer.

Long Term Options

Insulating gases (i.e. retained in foam, contributing to thermal insulation performance)

The 1991 Report identifies HCFC-124 as a potential substitute for CFC-12. Due to its limited commercial availability and ozone depletion it is no longer being evaluated for use in the extruded polystyrene insulation market.

HFC-134a

The PAFT testing programme has been satisfactorily completed. Ample amounts are now commercially available but the price is still unattractively high for significant quantities to be consumed in this industry where blowing agents represent an important share of production costs.

HFC-134a offers the following properties:

- thermal conductivity that is approximately 35 % higher than HCFC-142b;
- a boiling point of -26°C ;
- low permeability through polystyrene; it is believed to be similar to HCFC-142b;
- non-flammability; and
- a zero ozone depletion potential.

Another major drawback already identified is the poor solubility of HFC-134a in organic materials including polystyrene polymer. This causes severe processing difficulties and it is also questionable whether the insulation value achieved previously could be matched using HFC-134a alone.

Combined with its price, the above two factors virtually rule out any widespread use of HFC-134a in extruded polystyrene foam at this time.

Non-insulating gases (rapid diffusion out of foam, not contributing to thermal insulation)

HFC-152a

HFC-152a is an existing compound whose toxicological properties are known. Supplementary studies are not excluded, however.

One production unit operates on a commercial scale in the United States. Investment plans for a semi-industrial scale plant in France have also been announced.

HFC-152a has the following properties:

- since it has a high permeability through polystyrene, similar to HCFC-22, the 30% higher thermal conductivity than that of HCFC-142b really does not apply;
- a boiling point of -25°C;
- a flammability range in air that is 3.7% to 18% whilst the minimum ignition energy has been reported to be almost identical to that of hydrocarbons. (The value for HCFC-142b is two orders of magnitude higher); and
- a zero ozone depletion potential.

Bearing in mind the above properties and notwithstanding the fact that HFC-152a has been used in extruded polystyrene (XPS) sheet manufacture it does not seem likely that it will be used as a sole blowing agent for XPS boardstock. However, in combination with other substances, its use cannot be ruled out.

Hydrocarbons

Hydrocarbons, primarily butanes and pentanes, can be used to foam polystyrene. They have been used for many years in the manufacture of extruded sheet polystyrene foam packaging products in Europe, North America and Japan. Hydrocarbons are readily available and are relatively inexpensive compared with other blowing agent alternatives.

Extruded polystyrene boards can be satisfactorily produced with hydrocarbons alone. However hydrocarbons exhibit the following sometimes disqualifying disadvantages:

- hydrocarbons are flammable -- their safe handling and processing require that appropriate safety measures and significant capital investment be taken in the manufacturing plants, as well as in the distribution chain;
- hydrocarbon use can be subject to local air pollution regulations -- these regulations limit the emissions of volatile organic compounds, which contribute to tropospheric ozone (smog) formation;
- any appreciable amount of hydrocarbon retained in the foam seriously affects the performance of the product when subjected to even small-scale fire tests which, in many countries, are mandatory for construction materials; and

- consequently the practical level of hydrocarbon blowing agent is comparatively low.

Alcohols

Ethanol, like the hydrocarbons mentioned above can be used to make XPS boards. It is readily available, inexpensive and has zero ODP but shares many of the disadvantages of hydrocarbons:

- it is flammable;
- it is a volatile organic compound; and
- it has a high solubility in the polymer. Experience shows that ethanol cannot be used alone if foam collapse is to be avoided.

Ethanol diffuses rapidly out of the foam and therefore does not contribute to the insulation properties of the product. In at least one company in Europe ethanol is an established auxiliary blowing agent.

Atmospheric Gases

Where insulation performance is less critical but still important and where market forces are demanding it 100% CO₂ technology has been introduced in Germany and northern Europe on a limited basis for extruded polystyrene board insulation products.

Zero ODP products not using 100% CO₂ but CO₂ in combination with one or more of the above mentioned options are also commercially available on a limited basis in the same geographic area.

Recovery/Recycle/Destruction

At present, there are no recovery processes known to be in use in extruded polystyrene boardstock facilities. There are several reasons why this option has not been considered technically and economically feasible in the past.

An estimated 75% to 85% of the HCFC/CFC-blowing agents are trapped within the cells of the finished product. Thus, only 15% to 25% of the blowing agents consumed are available for capture.

Currently, it appears that carbon adsorption and molecular sieves offer the best possible capture technology. Several technical problems will need to be overcome first to successfully recover HCFCs. These problems include:

- Collection -- blowing agent emissions occur at several points in the process. A large portion of the plant air must be collected in order to capture most of the HCFCs;

- Capture -- plant air streams are quite dilute, making efficient adsorption on carbon more difficult. The use of auxiliary blowing agents can interfere with the efficient capture of the HCFCs. Contaminants in the plant air stream can interfere with the adsorption capacity and lifetime of the carbon bed and molecular sieve; and
- Recovery/ Destruction -- HCFCs used in the manufacture of extruded polystyrene foam boardstock have low boiling points and thus complicate the separation from water (ice formation) and other contaminants in the air stream. Proven technology for destruction of CFC's/HCFC's in foams is incineration. Suitably equipped municipal solid waste incinerators are UNEP approved destruction technology for ODS in foams.

Product Substitutes

Foam insulation provides high energy efficiency combined with other physical properties. These include excellent fire-test performance, waterproof characteristics, low density, thin profile, and ease of handling. Other insulating products, such as expandable polystyrene bead board, cellular glass board, perlite board, fibreboard and gypsum board, can provide some of these properties, but not all. Consequently, these substitute products may not be considered alternatives for all applications of extruded polystyrene insulation foam.

When a substitution is made, the alternative material will often have a higher thermal conductivity per unit thickness, and hence will not insulate as efficiently as the foam insulation of equal thickness blown with HCFC-142b. It is necessary to increase the thickness of the alternatives to compensate for lower insulating values. Here either the economic impact or the capacity to comply with demands on physical dimensions required by the application in question may be decisive factors. If a less efficient insulation configuration is selected, energy consumption increases with subsequent increases in fossil fuel consumption. CO₂ emissions will rise with a recognisable impact on global warming.

The main difficulties in using alternative insulating products are in applications where the waterproof characteristic of foam insulants is a major advantage. In these uses, which are typically applications of extruded polystyrene insulation foam, there is no obvious alternative without considerable changes in design and construction practice (Curwell and March, Hazardous Building Materials 1986).

Phaseout Schedule

Based on the available alternative blowing agents, the extruded polystyrene foam board industry has, in the developed world, completed, as expected, the phase out of CFC's by end of 1993.

Conclusions

HCFC-142b (alone or in combination with HCFC-22) represents the most practical option to CFC-12 in extruded polystyrene board insulation.

Although unproven, recapture and recovery technology is being actively investigated to solve several technical problems. About 15 % to 25 % of the initial HCFC charge is released during manufacturing process.

Government support and encouragement are essential in non-Party and developing countries to ensure a timely exit from CFC's.

Conversion to HCFCs will maintain the long-term insulation performance of extruded polystyrene boardstock, but some other product properties may be negatively affected. Using HCFCs achieves at least a 90 % reduction in ozone depletion potential and at least an 85 % reduction in greenhouse potential from this industry segment.

Successful conversion to other alternatives requires considerable technology, which means that smaller manufacturers will have greater resource difficulties.

It is recognised that there will be an ultimate need to use zero ODP insulating gases in applications where high thermal performance is required.

Some substitution to non-insulating gases is occurring where either superior thermal performance is not the most critical factor or market forces demand this type of product or both.

Chapter Six

POLYOLEFIN FOAMS

Products and Applications

The general category of polyolefin foams includes products made from either polyethylene or polypropylene resins. These general foam types sometimes include other olefinic constituents, such as ethylene/vinyl acetate or ethylene/acrylic acid copolymer resins, as modifiers. Several different manufacturing processes are used for polyolefin foams, which result in different product forms.

One type of processing, which involves the crosslinking of extruded resin sheet and its subsequent expansion, uses only decomposable blowing agents, such as azodicarbonamide, and, as such, this process will not be considered further here. These products have different properties and are typically more expensive than polyolefin foams manufactured with CFCs. They are not generally considered to be substitutes for most non-crosslinked polyolefin foam applications.

Polyethylene and, more recently, polypropylene resins are used in expandable bead products, which may be subsequently shape-moulded. These foam products are used primarily as moulded cushion packaging and automotive bumper systems. CFC-11 and CFC-12 were previously used as blowing agents. All bead producers now use hydrocarbons or carbon dioxide. Consequently, no further comments will be made regarding these products.

Both polyethylene and polypropylene resins are extruded into sheet products. These sheet products are commonly used as protective packaging for furniture, electronic devices, and other goods. Other applications include flotation devices (such as life vests), construction materials, and gaskets. CFC-11, CFC-12, and CFC-114 have historically been used for most of these sheet products.

Polyethylene resins are used in the manufacture of extruded plank products. Their most frequent application is designed cushion packaging of electronic or other high-value goods. Some plank products are also used in military packaging, flotation, construction, aircraft seating and other applications. CFC-12 and CFC-114 were generally used in the manufacture of plank products.

Polyolefin foam is also extruded in an annular shape (tubing) for use as thermal insulation for pipe. Applications include residential hot and cold water pipe insulation and similar near-ambient and cold temperature applications. Historically CFC-12 or CFC-114 were used as blowing agents.

In most polyolefin foam applications, products are used because of specific properties. The most important of these properties is the material's ability to provide insulation from mechanical, vibrational, thermal and/or other environmental stresses.

A good example is the packaging of military hardware. Items, such as missiles deployed on land, sea or air are shipped from the manufacturer, through the distribution system, to the ultimate field unit. The package is specifically designed to insulate the device, containing both explosives and sophisticated computer and guidance hardware, from a broad range of possible conditions. These include the mechanical and vibrational stresses due to rough handling and transportation under rugged conditions, moisture and humidity, sand and dirt in temperatures varying from arctic to equatorial extremes. The package can be made entirely of polyolefin foam with only straps to secure it or may consist of foam inserts inside a container. Similar considerations apply to civilian consumer applications, although often under less severe conditions.

An additional benefit of these resilient materials is their reusability. In many applications, the packaging materials may be returned to the manufacturer to package new goods without degradation of performance. This multiple reuse is a good example of the proper use of plastic materials to conserve raw materials. In addition, fabrication trim scrap is often returned to the foam producer for reuse in the process.

Production Processes

In the case of extruded products, the resin is melted and mixed with the blowing agent(s). The resin and blowing agent are then passed through a die, where the product rapidly expands and cools. For sheet products, a circular, annular die is used to form a thin-walled hollow cylinder of foam. This foam tube is subsequently slit to produce a flat sheet that can then be rolled for storage or shipment. Sheet products are normally no thicker than 13 mm, and most are no thicker than 6 mm.

Pipe insulation also uses an annular die but one producing a reasonably small diameter, relatively thick-walled foam product. The inside diameter of the tubing ranges from 6 mm to 125 mm with wall thicknesses of 5 to 50 mm.

Typically, plank products are made using a specific die, which produces the particular cross-section desired. Each cross-section requires a different die. The plank is then cut to length and, if necessary, the edges are trimmed. Plank products can be from 12 to over 100 mm thick, and are made up to 1200 mm wide. They are occasionally made in circular or other non-rectangular cross-sections. One process injects the foaming materials into a closed cavity to help dimension the product.

All three foam types are closed cell products. Thus, most of their blowing agents are initially trapped within the foam. With very thin sheet products, a significant portion of the blowing agent may be lost at or near the die. For extruded plank, tubing and thicker sheet products, very little is lost at the die although some will be lost in trimming operations, which open the cells.

Global Consumption of CFCs in Polyolefin Foams

For 1993 the total consumption of CFCs by this industry segment has been estimated to be 910 tonnes. This is a decrease of 93 % from that previously reported for 1990 and 95 % from 1986. It is possible that additional CFC usage may have occurred in 1993 since gathering consumption statistics in developing countries is extremely difficult.

Rapid progress continues to be made in eliminating the use of CFCs in all product types. Many extruded products have been converted to HCFC-22, HCFC-142b, HFC-152a, hydrocarbons and/or carbon dioxide. All manufacturers of mouldable bead products have converted to hydrocarbons and/or carbon dioxide combined with pre-expansion. By the end of 1994, virtually all remaining CFC use in polyolefin foams, estimated at 600 ODP tonnes per annum, will be in developing countries.

Global Consumption of HCFCs and Projected Growth

An estimated 250 ODP tonnes of HCFCs were used in 1993 in this industry segment. Many manufacturers, who had previously switched to HCFCs, have now converted to zero ODP substances. Most commonly, these are hydrocarbons or hydrocarbon/HFC-152a blends. The Clean Air Act Amendments of 1990 in the USA bans the use of all ODSs in all foams except those used for thermal insulation or automotive safety cushioning. This eliminated all use of HCFCs in polyolefin foams, except for pipe insulation, beginning January 1, 1994. Many European countries, including the European Union, are restricting use of HCFCs in similar products. Most developing country producers will be switching directly from CFCs to zero ODP options with the assistance of multilateral funding support. An estimated 180 ODP tonnes per annum of HCFCs will be in use by this industry segment at the end of 1994.

Technical Options to Reduce Ozone Depleting Compounds in Polyolefin Foams

One of the primary criteria in blowing agent selection is the ability to match the diffusion rate of blowing agents out of the foam with the diffusion rate of air into it. This match is necessary because the polyolefin resins are resilient. If the diffusion rates are not sufficiently matched, the foam will either shrink or grow while aging. This is unacceptable in all three product types. Permeability modifiers can sometimes be used to help match these diffusion rates where they are reasonably close but not acceptably so.

Current Options

The threat of early elimination of HCFCs was the cause of great concern for some industry segments where no clear alternative existed. Indeed, it actually retarded the conversion from CFCs to HCFCs, producing an overall negative environmental impact, since the potential cost and the strain on resources of two rapid conversions is a heavy burden on many manufacturers in highly competitive markets.

Reduced ODP

HCFC-22

HCFC-22 has a very low boiling point and, consequently, a high vapour pressure. This characteristic limits its use to the manufacture of some thin sheet products. Thicker sheet and plank products are extremely difficult to make with HCFC-22.

HCFC-142b

HCFC-142b has been the preferred alternative for thicker sheet, pipe insulation and plank products. It has a minimal flammability which does not affect the fire safety of the material produced with this blowing agent. The permeation rate through polyethylene is close enough to air to provide a dimensionally stable foam through use of permeability modifying additives.

Sometimes HCFC-142b is used with HCFC-22 to make a non-flammable blowing agent mixture, which is often used to manufacture pipe insulation products.

Zero ODP

Hydrocarbons

Hydrocarbons are flammable. For example, isobutane flammability limits are about 1.8 to 8.4 volume percent in air with an extremely low energy of ignition. This situation requires the careful consideration of equipment and procedures in manufacturing, storage, handling, and shipping as well as local regulations and the possible effects on customers. Some mouldable bead product suppliers use hydrocarbons in a closed pre-expansion process which captures essentially all of the gas.

In addition, in the United States, such hydrocarbons are classified as volatile organic compounds (VOCs, considered to be precursors to ground level ozone or "smog") and, therefore, are subject to regulations limiting plant emissions. Some European countries are considering similar regulations. Because the hydrocarbons would be released in very dilute concentrations from storage areas, collection of these gases could be inefficient and prohibitively costly (see Recovery/Recycle section below).

In some instances, significant plant modifications are required to handle these blowing agents. In others, the manufacturer may be unable to use flammable blowing agents for safety and handling reasons or because of local air pollution or flammability regulations.

Some manufacturers have converted, or expect to convert, from CFCs to hydrocarbons.

HFC-152a

By itself, HFC-152a is difficult to use in making large cross-section polyolefin foams. Consequently, it is used primarily in combination with hydrocarbons. Whilst the lower flammability limit of HFC-152a is higher than isobutane (3.7% vs. 1.8%), it has a similar low energy of ignition and must be handled much like the hydrocarbons. It is not considered to be a VOC in the US and can thus be used to meet plant emission requirements.

HFC-134a

HFC-134a is even more difficult to use than HFC-152a. However, its zero ODP value and lack of flammability has led to some use, primarily in Japan where it is used in conjunction with other blowing agents such as isobutane or ethyl chloride. The present cost of HFC-134a is prohibitive for many producers.

Long Term Options

Since all polyolefin foams, with the exception of pipe insulation (because of fire safety reasons when installed in buildings), can convert to one of the current zero ODP options, the long term options will be preferred primarily for characteristics other than zero ODP. Flammability or environmental concerns with some of the current options may lead to a later conversion to one of the materials below.

Carbon Dioxide and Other Inorganic Gases

Carbon dioxide (CO₂), nitrogen and other inorganic gases have very low solubility in the resins and may be of only limited use in extruded foams of these types. In addition, process pressures will be very high, perhaps beyond the capability of some processes without significant or prohibitive capital expenditure. These volatile gases are, however, being used in some mouldable bead products where the process pressure problem can be overcome. Carbon dioxide diffuses rapidly out of polyolefin foams and could cause massive dimensional stability problems without some, as yet unidentified, enabling technology.

In making any conversion, a manufacturer must weigh the costs and benefits of the conversion. Necessary capital expenditures, raw material cost and availability, environmental considerations, conversion efficiency, achievable range of foam products and foam properties must all be considered. Few generalisations can be made except that any of the above can greatly affect the ability to succeed in these highly competitive markets. Likewise, no one solution will be applicable to all producers since various specific factors listed above may affect the viability of a particular option for that manufacturer.

Recovery/Recycle/Destruction

Recovery feasibility is primarily a function of product thickness and type. Some mouldable bead product suppliers use hydrocarbons in a closed pre-expansion process which captures essentially all of the gas. In extruded foams the permeation rate of blowing agents out of the foam is inversely proportional to the square of the product thickness. In very thin products, a major portion of the blowing agent is expelled at or near the die and can be captured fairly easily. One producer of very thin polypropylene foam sheet products is currently capturing and recovering blowing agents at better than 95 percent efficiency.

For thicker sheet, tubing, and all plank products, collection of the blowing agents to any significant extent is often difficult and, consequently, very expensive. In these cases, the blowing agent captured within the cell walls of the foam leaks slowly over a period of days, weeks, or months and is lost during warehousing, shipment, and even use of the foam. This implies that a large volume of air with very dilute gas concentrations must be collected and only a portion of the blowing agent will be recovered prior to shipment.

When air streams containing organic vapours are captured, the contaminant can be removed by carbon adsorption. The efficiency of such operations depends on the concentration of vapours in the air (higher concentrations generally mean greater efficiency). Except in the case of very thin foams, which lose a large quantity of blowing agent near the die, these air streams are quite dilute. This characteristic dramatically increases the cost and difficulty of efficiently recovering organic blowing agents. In addition, foam plant ambient air has a significant level of moisture. This complication hinders the recovery of blowing agents with low boiling points (ice formation).

In the case of hydrocarbons, the gas in the air stream can be removed by incineration. However, because the gas concentration is very dilute, additional fuel must be added to sustain combustion. This is not only an added operational expense but of questionable environmental value.

Where a manufacturer has a need for steam, the air stream can be used as the air supply for the boiler. However, large quantities of air must be processed to remove the hydrocarbons and may be in excess of the demand for steam, and thus an added cost to the business.

Product Substitution

In many applications of polyolefin foams, products are used because of their specific properties. Whilst materials such as paper, cardboard, and expanded polystyrene can be used in some packaging applications, they are not effective substitutes in most applications of polyolefin foams. However, because most polyolefin foam segments have already, or are nearly, converted into zero ODP alternatives, there is little need for product substitution to eliminate stratospheric ozone depletion concerns. All mouldable bead producers have eliminated use of ozone depleting substances.

Conclusions

For calendar 1993, approximately 95 % of CFC usage had been eliminated in polyolefin foams compared to the 1986 base (910 tonnes vs 19000 tonnes). Some use of HCFCs also existed and is estimated at 250 ODP tonnes. By the end of 1994 it is estimated that 96 % conversion had occurred for a further reduction to an annualised rate of 780 ODP tonnes (CFCs: 600; HCFCs: 180). At that time, all remaining CFC usage is expected to be in developing countries. Several MLF projects are in development to address this use. In general, this industry segment is rapidly moving out of all ODSs.

Some options might be useful in foam sheet products alone. This is because the loss of blowing agents is strongly related to product thickness and so aging time for very thin products might be acceptably short.

A number of different processes are employed in the manufacture of polyolefin products, and the resultant foams are used in a variety of applications, primarily in protective cushion and military packaging, flotation, pipe insulation, and construction. The most important property of these foams is their energy absorbing characteristics which allow insulation of items from mechanical, vibrational, thermal and/or environmental stresses. Many polyolefin foams are used for their specific performance characteristics, thus limiting the economic viability of substitution of other products. The rapid movement of this industry segment out of ODSs minimises the need for product substitution.

Due to the performance demands of the applications, the resulting foam properties of these substitutes do not differ greatly from those of the current products. It is necessary for the manufacturer to adjust his formulation and processing conditions, however. This affects costs and increases the difficulty of making a conversion. Possible interferences with additives used for anti-static, flame retardant, coloring or other purposes may be an additional barrier to use of some alternatives in specific products. For all of the above reasons, a manufacturer must select the best option for his business. No one solution is expected to be optimum for all producers in an industry segment.

Because these foam products are made in a variety of shapes and for different applications, it may take an extended period of time for a manufacturer to make a complete conversion of an entire product line. Most of these foams are performance products which must maintain specific properties to be useful in each application. This will require extensive product development and testing by both the manufacturer and customer prior to plant conversion.

The uncertainty about the long term viability of HCFCs in this application slowed the conversion out of CFCs, particularly in developing countries. Similar concerns with some of the currently available options could have a similar effect in the future.

Appendix A

UNEP FOAMS TECHNICAL OPTIONS COMMITTEE

Committee Member	Affiliation	Country
Mr. Godfrey Abbott	Dow Europe/Exiba	Switzerland
Mr. Paul Ashford	BP Chemicals Ltd./EPFA	United Kingdom
Ms. Lorraine Aulizio	Celotex Corporation/PIMA	United States
Ms. Marion Axmith	The Society of the Plastics Industry, Inc.	Canada
Mr. Craig Barkhouse	Foamex Canada/CFFMA	Canada
Dr. Gert Baumann	Miles Inc.	United States
Dr. Ted Biermann	BASF Corporation	United States
Mr. Michael J. Cartmell	ICI Polyurethanes	United States
Mr. John Clinton	NRG Barriers/PIMA	United States
Mr. Hubert Creyf	Recticel/Europur	Belgium
Mr. Shi Jia Fan	Qindao Haier Group Company	China
Dr. Alan Fine	U.S. Environmental Protection Agency	United States
Mr. Ryoichi Fujimoto	Hitachi Ltd.	Japan
Mr. Reg Hurd	British Rubber Manufacturers Association	United Kingdom
Dr. Mike Jeffs	ICI Polyurethanes	Belgium
Dr. Robert Johnson	Whirlpool	United States
Ms. Fran W. Lichtenberg	The Society of the Plastics Industry, Inc.	United States
Mr. Yehia Lotfi	Technocom	Egypt
Ms. Jean Lupinacci	U.S. Environmental Protection Agency	United States - Chair
Mr. John Minsker	Dow Chemical	United States
Ms. Sally Rand	U.S. Environmental Protection Agency	United States
Mr. M. Sarangapani	Polyurethane Council of India	India
Mr. Muneharu Sanoh	The Japanese Electrical Manufacturers Association	Japan
Dr. Ian R. Shankland	AlliedSignal	United States
Mr. Sodario Souto	Brastemp S.A.	Brasil
Mr. Bert Veenendaal	RAPPA Inc.	United States
Dr. Udo Wenning	Bosch-Seimens Hausgerate GMBH	Germany
Mr. Takao Yamamoto	Japan Urethane Foam Industrial Association	Japan